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AIRCRAFT MEASUREMENTS AND ANALYSIS OF SEVERE STORMS

1976 FIELD EXPERIMENT
FINAL REPORT



Principal Investigator: P.C. Sinclair .

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DEPARTMENT OF ATMOSPHERIC SCIENCE
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

AIRCRAFT MEASUREMENTS AND ANALYSIS OF SEVERE STORMS:
1976 FIELD EXPERIMENT

FINAL REPORT

NSG-5105: NASA Severe Storm Surveillance Program

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ABSTRACT

This Final Report covers the period 1 March 1976 - 1 July, 1977 and documents the severe storm aircraft measurements obtained during the 1976 Spring storm season as well as the instrumentation and operational features of the aircraft mobility capabilities in support of the NASA's Severe Storm Surveillance Program (SSSP). The measurements and data analyses indicate that the concept of a highly mobile research aircraft capability for obtaining detailed measurements of wind, temperature, moisture, spherics, etc. near and within severe storm systems, forecast 48 hours in advance in a 1000 nm operating radius, is not only feasible but now has been successfully demonstrated during both the 1975 and 1976 SSSP's. The 1976 measurements and analyses reveal several new severe storm features and insights with respect to storm air flow circulations and inflow-outflow orientation, i.e.

- (1) Precipitation downdraft air is recirculated back into the updraft core below the scud cloud in both back-and front-feeder type storms.
- (2) In a back-feeder type storm, the downdraft outflow air ahead of the storm may also recirculate back into the updraft region near cloud base.
- (3) The detection of a subcloud vortex indicates that sufficient vorticity (vertical component) may be readily available in the near storm environment due to the interaction of the outflow-inflow circulations.
- (4) Mid-level upstream measurements indicate little or no environmental air inflow to the backside of the storm cells or line squalls investigated.
- (5) Over a 24 hour period, storms formed ahead of a frontal disturbance can change from front-feeder to back-feeder types.

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I wish to express my appreciation to the many people who were collectively responsible for the ultimate success of this severe storm field measurement program. As a matter of record, the key personnel that were responsible for the aircraft and instrumentation development, the field operations, and the data analysis and interpretation are listed below along with their primary work area responsibility(s):

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I. Introduction

During the spring and summer of each year, the eastern half of the United States experiences violent squall line and tornadic storms that kill hundreds of people and result in many millions of dollars damage. As the population density in the U.S. increases, the number of deaths and property damage will increase markedly. Consequently, a significant increase in our understanding of severe storms by direct observations is urgently needed to assist the development of adequate ground and/or satellite based warning systems and the design of safe homes and buildings. This information is especially pertinent with respect to the design of potentially hazardous structures such as nuclear power plants and toxic chemical plants or depots.

A. Project Objectives

The purpose of the present research has been to gain a clearer insight into the severe storm structure and life-cycle by direct cloud penetrations and environmental measurements with three specially instrumented atmospheric research aircraft. This research is a natural extension of our previous storm and analysis programs. The first three sections of this report present an overview and aircraft-instrumentation outline of the CSU program support to the NASA, Severe Storm Surveillance Program (SSSP). The latter sections (IV-VI) contain specific information on the 1976 Spring field program.

The aircraft measurement program is specifically designed to accomplish the following two-fold objective:

1. Determine from aircraft measurements the storm near-environment circulation and the vertical motion and temperature fields at several levels from the ground to approximately 40,000 ft. MSL. Three special research aircraft are to be employed; one in the sub-cloud region, one at mid-levels outside the visible convective cell, and

another within the cloud above 15,000 ft. MSL. The flight profiles of the three aircraft will provide the necessary measurements of cloud near-environment circulation, in-cloud vertical velocity and buoyancy, and sub-cloud inflow and vertical motion structure. These measurements are designed to further our understanding of the mechanisms controlling cloud growth and life-cycle, overshooting cloud tops as observed by satellite, and tornado vortex initiation.

2. Determine from aircraft measurements the dynamical-thermodynamical properties of the storm updraft-downdraft region in order to formulate a more quantitative descriptive model of severe storm initiation, growth, and dissipation phases. Formulation of such storm model components will permit mathematical synthesis of more complete theoretical models in the future. With these model(s), a systematic study can be made of the storm energy budget and factors which might control storm development and intensity. The final goal is to develop refined severe storm models which will bring into sharper focus those severe storm-tornado features or characteristics (i.e., tornado cyclone signatures) which can be observed and monitored by satellites.

B. Aircraft and Instrumentation Systems

1. Aircraft and Altitude Location

In order to accomplish the desired goals, the CSU Severe Storm Measurement and Analysis Group (SSMAG) has instrumented, calibrated, and deployed the following three specially equipped atmospheric research aircraft with flight and ground support crew::

- a) McDonnell F101B severe storm penetration aircraft
(15,000-40,000 ft. MSL): Fig. 1.
- b) Beech Queen Air B-80 mid-level environmental aircraft
(15,000-25,000 ft. MSL): Fig. 3.

Fig. 1: Upper Level Severe Storms Measurement Aircraft

The McDonnell F101B jet interceptor has been extensively modified to carry the AADS-4A system. In order to preserve the excellent radar system (MG-13), the nose instrumentation boom was installed above the radar antenna in an area previously occupied by IR or refueling equipment. The boom and supporting structure have been designed with ultimate load factors in excess of the aircraft. The total length of the boom is approximately 16 ft, with 9 ft of the boom projecting ahead of the aircraft. At present, the gyro-reference system, transducers, and all associated electronics are housed in a temperature controlled chamber in the nose of the aircraft. This system is being updated with the installation of an inertial platform in the aircraft missile bay. The missile bay is located on the bottom of the aircraft directly below the cockpits. Its size (7.0' x 4.0' x 2.5') the temperature controlled environment make it an ideal instrumentation location.

The aircraft is equipped with UHF, VHF, and FM radio communications. Either TACAN, VOR-DME or VLF can be used for navigation. With one 450 gal. drop-tank and internal fuel, the aircraft can remain on station for approximately 2 hrs. Two drop-tanks can be carried, but storm penetrations are normally made "clean" or with one drop-tank due to superior flight characteristics.

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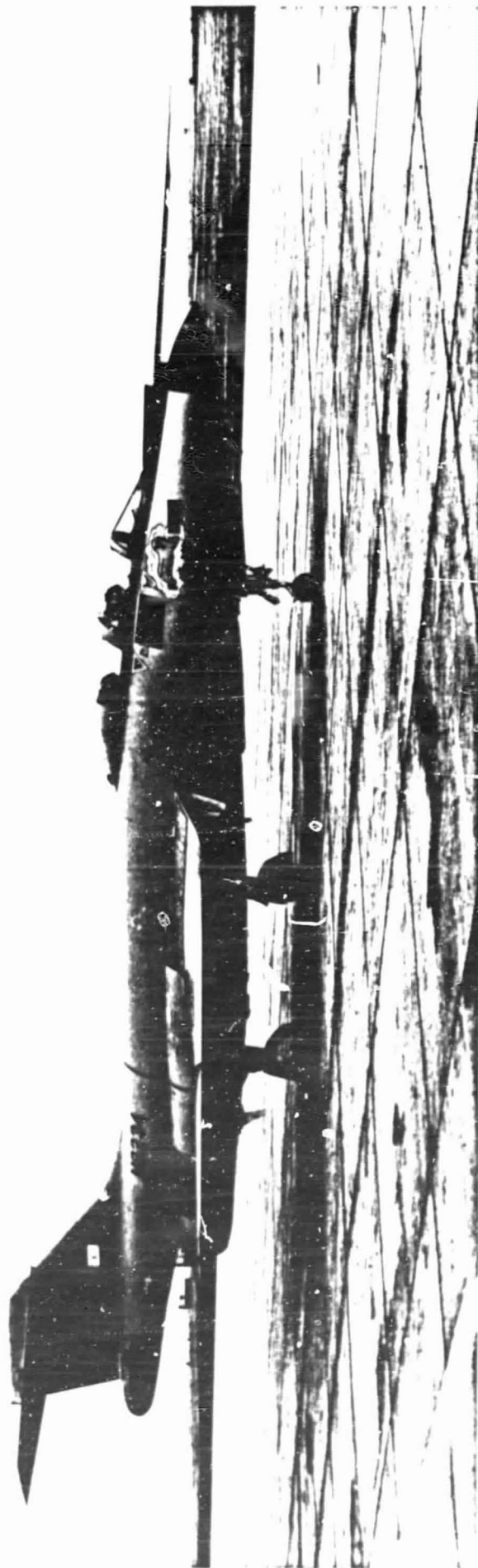


Fig. 3: Mid Level Severe Storms Measurement Aircraft:
Q.A. B-80

The Q.A. B-80 research aircraft and AADS-5A is capable of measuring and recording the pressure, temperature, dew point and mid-cloud environmental wind. The horizontal mean winds are obtained from a doppler wind system (AN/APN153V) located in the rear of the aircraft. The antenna radome is shown (Fig. 3) aft of the wing on the bottom of the fuselage. A forward pointing radar in the nose is used to initially locate the storm for optimum cell intercept and to establish the optimum flight track(s) around the storm. Seven antennas have been added to the aircraft fuselage in order to monitor the storm lightning discharge spectra in the 3-300 MHZ frequency range. Approximately 400 lbs of receivers, power supplies, and recording systems are carried internally to support this NASA piggyback experiment.

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- c) North American (N.A.) T-28 sub-cloud aircraft (sfc - 15,000 ft. MSL): Fig. 4.

All aircraft have similar instrumentation systems and sufficient performance to provide extensive overlap in measurement capability near and within the storm cell.

2. Instrumentation Systems: AADS-2B-5A

(a) F101B Severe Storm Penetration Aircraft: AADS-4A

SSMAG has developed several Airborne Atmospheric Data Systems (AADS-3B-4A) for direct measurement of the three-dimensional velocity field, temperature, and pressure in severe storms between 16,000 to 42,000 ft. MSL. The measurement system is designed so as to be independent of the aircraft sensitivity to atmospheric motions and/or pilot induced motions. The measurement technique (Sinclair, 1969, 1973) requires knowledge of the air motion relative to the airplane ($V_{a,p}$) and the motion of the airplane relative to the ground ($V_{p,g}$) in order to calculate the atmospheric motion with respect to the ground ($V_{a,g}$) i.e. from Fig. 2:

$$V_{a,g} = V_{a,p} + V_{p,g}$$

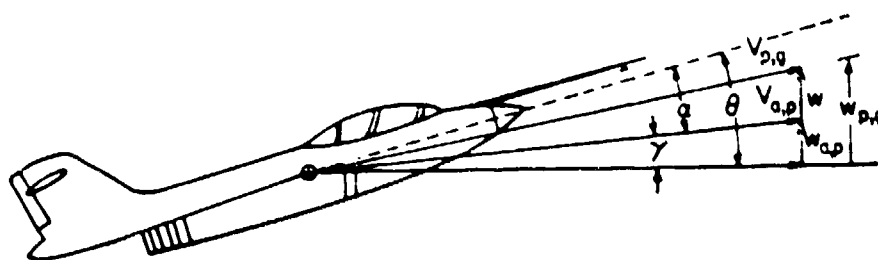


Fig. 2: Relationship of vertical velocity measurement system and aircraft flight axes

Using the small angle approximation, the vertical component ($W_{a,g}$) can be expressed as:

$$W_{a,g} = W_{p,g}(0) + V_T \alpha + V_T \beta \phi - V_T \theta + \int_0^t a_z dt + L \dot{\theta}$$

Fig. 4: Sub-Cloud Severe Storms Measurement Aircraft:
N.A. T-28

The North American T-28 aircraft has been extensively modified to carry the AADS-2B system. The boom structure positions some of the sensing probes ahead of the aircraft propellor to minimize fuselage flow and pressure anomalies. The boom supports the Rosemount pitot-static tube and the α - β vane system. The α and β vane units, along with the gyro referenced platform, provide data on the vertical and lateral air motions near and within the severe storms. The balsa vane are coated with a special abrasive coating and are internally mass balanced to improve the response characteristics. The boom is of aluminum-stainless steel construction and has a natural frequency of 11 cps. A doppler wind system (APN-153V) is located below the observer (bottom of the fuselage) for obtaining sub-cloud and shear-line wind measurements.

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where V_T is the true air speed; α the angle of attack, θ , β , and ϕ the pitch, yaw, roll angles, respectively; a_z the vertical acceleration of the aircraft; $W_{p,g}(0)$ and vertical motion of the aircraft at time $t = 0$; $\dot{\theta}$ the pitch rate; and L the accelerometer displacement from the angle of attack measurement point. The measurement of α and β are made with lightweight, but durable flow vanes. The flow vanes and pitot system are mounted on a nose-boom in front of the aircraft to minimize the affects of fuselage induced flow fields. As in all nose-boom designs, the length of the boom is always a compromise between boom natural frequency, size, structural integrity, and complete removal of upwash and pressure errors. The boom natural frequency requirement of 12 Hz and the available aircraft mounting location specified the boom size. Upwash and static pressure errors have been removed by careful tower fly-by calibrations and aircraft intercomparison flight tests. Dynamic response characteristics of the vane-pitot tube system were accomplished by programmed pitch-roll flight tests (roller-coaster maneuvers). These calibrations and flight tests indicate that the AADS-4 system has the following mean error bands:

$$\Delta u = \Delta v = \Delta w = \pm 0.5 \text{ msec}^{-1}; \Delta T = \pm 0.3^\circ\text{C}; \Delta P = \pm 0.005 \text{ psi}$$

The pitch (θ), pitch rate ($\dot{\theta}$), roll (ϕ), and yaw (β) angles are measured by precision vertical, rate, and heading gyros located in an environmentally controlled temperature chamber in the nose of the aircraft.

Aircraft accelerations are monitored by a three-axis accelerometer system mounted at the aircraft c.g., and the true airspeed is calculated from measurements of total pressure, static pressure, and total temperature. The static temperature and true airspeed are determined by use of the compressible, subsonic flow equations (Sinclair, 1973).

$$\frac{P_t - P_s}{P_s} = \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} - 1$$

$$\frac{T_t}{T_s} = 1 + \frac{\gamma-1}{2} \xi M^2$$

$$V_t = T_t^{1/2} \left\{ \gamma R / \left(1 + \frac{\gamma-1}{2}\right) \right\}^{1/2}$$

where: P_t = total pressure; P_s = static pressure; M = Mach number;
 T_t = total temperature; T_s = static temperature; ξ = recovery factor;
 γ = ratio of specific heats of air; c_p/c_v ; V_t = true airspeed.

Relatively fine structure of the turbulent velocity and temperature spectrum (0.04 to 10 hz) can be obtained from the twenty channels of data which are recorded on a 1000 character per second, digital, incremental magnetic tape recorder. The fast response sensors are sampled every 0.02 sec. while the slower responding instruments are sampled every 0.04 sec. The AADS-4A systems control and recording center is located in the rear cockpit of the F101B in front of the flight director. Eight-pole Butterworth filters are used in the AADS-2, 4 systems to remove data fluctuations with frequencies higher than 10 hz. In addition, similar digital filtering is employed in the computer processing of the raw data prior to converting the digital signals to engineering units. This provides an effective filter system for removing nose-boom vibrations errors, internal electronic noise, and aircraft systems noise.

Since ground research radars are not normally available to determine the location and intensity of cloud reflectivity zones prior to penetration, the F101B MG-13 fire control radar has been used to provide the necessary radar surveillance of the storm. During the first year (1975) of field operations, it became very apparent that without suitable radar probing of the storm prior to penetration only relatively small clouds

could be selected for study. We are still in the process of completing the MG-13 modification in order to provide iso-echo contouring and gain selection. The reflectivity contouring capability will provide a better estimate of the location of the high reflectivity core of the storm.

(b) Queen Air B-80 Mid-Level Cloud Environment Aircraft:
AADS-5A

The B-80 was specifically acquired for the SSSP program and it was, therefore, outfitted with a new instrumentation system (AADS-5A) with the same capabilities as the AADS-4A in the F101B. This is a complete system installation which includes all sensors, interface units, and digital recording system. In addition, five special antennas and a large (450 lb.) spherics data system has been installed to support the NASA Goddard severe storm radio emission (3-400 Mhz) spherics research; P.I. Dr. David Levine with Dr. B. Wilson acting as field scientist for Georgia Tech. (NASA subcontractor). Because of the B-80's lower altitude flight profile, a doppler radar wind system has been used in place of the F101B's VLF system. The doppler wind system and the primary DME system provides a dual wind measurement system for higher accuracy and back-up redundancy. While this dual system is not as accurate as an inertial system, it provides horizontal wind measurements every 1-3 km (depending on aircraft type) with an accuracy of approximately $\pm 1 \text{ msec}^{-1}$ at about 10% the cost of an inertial system.

(c) N.A. T-28 Sub-Cloud Research Aircraft: AADS-2B-C

Over the past six years we have developed aircraft measurements systems and flight crews that are capable of severe storm sub-cloud flight profiles in the most severe flight environments. In all cases these systems have been installed in military type aircraft that are sufficiently strong to withstand the possible severe turbulence

and hail encountered in this region. Considerable experience from previous flight programs indicates that only military type aircraft (stressed to at least +8 to -5 g ultimate) are reasonable choices for the sub-cloud flight regime. The use of business-type twin engine aircraft, which is very prevalent, in the sub-cloud region is so dangerous to warrant this note and to further reiterate the use of only highly stressed aircraft for investigations in this region. Simply the loss of the windshield by hail damage in many of the commercial type single and/or twin engine aircraft could mean the loss of the aircraft and crew. Hail damage received by both the penetration and low-level aircraft in the past substantiate this conclusion. Note that the mid-level B-80 aircraft is VFR and laterally displaced from the visible storm cell by at least 5-10 miles in order to remain outside of the hail zone.

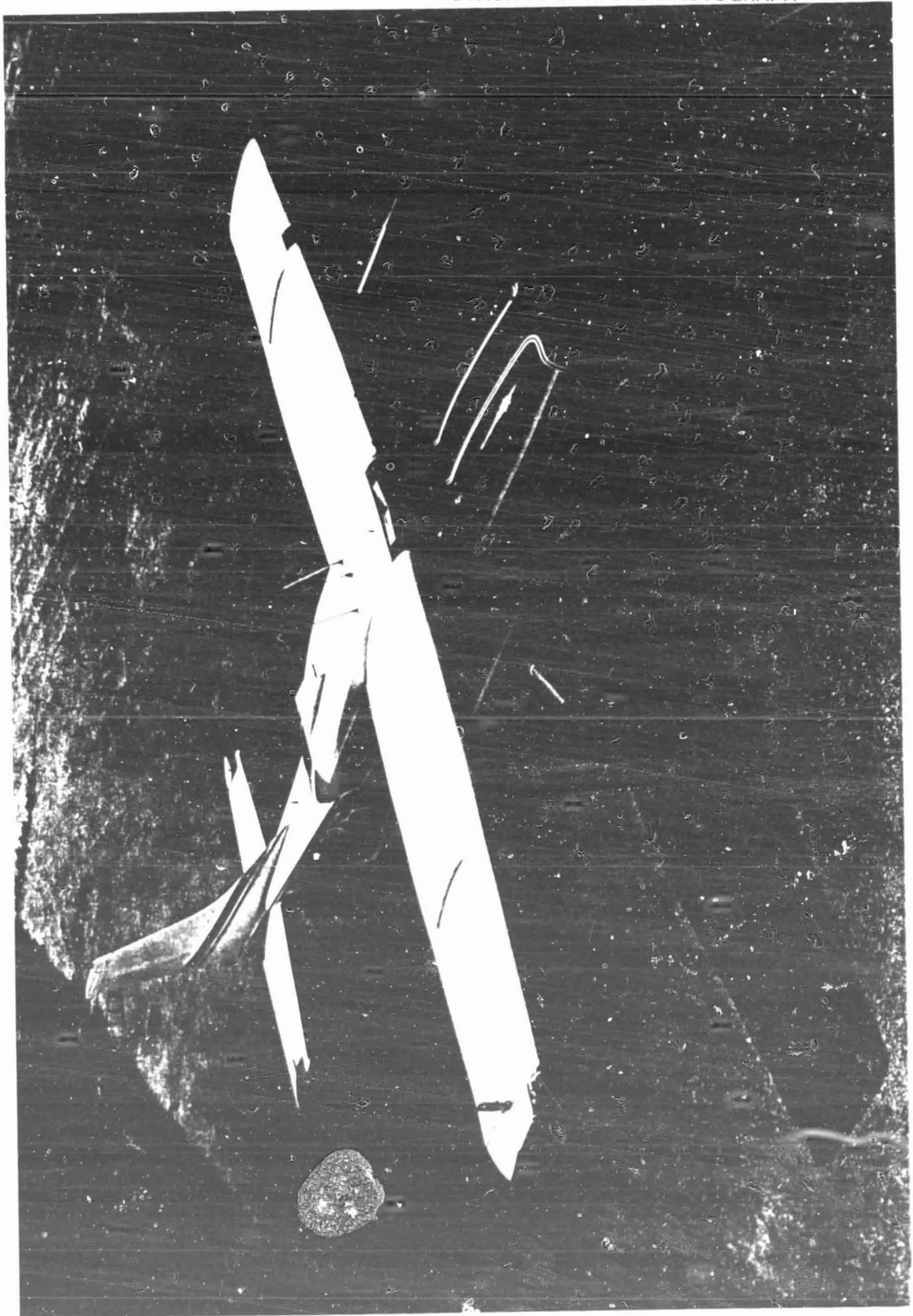
In order to satisfy the NASA mobility requirements, we purchased a North American T-28 (Hamilton Conversion) aircraft (Fig. 4). This N.A. T-28 is a standard normal category aircraft stressed to +13 g, -8 g that will cruise at over 210 mph and have an on-station research time of approximately 5 hours. We have updated the T-6, AADS-2B system and installed it on the T-28B in the same configuration, i.e. the instrumentation pod-boom system is mounted on the hard points of the right wing. A DME-doppler wind system similar to the B-80 system is also installed, along with a dew point hygrometer and the radio altimeter. All T-28 and B-80 systems have the same accuracy and precision as the F101B system, and in addition they also have a greater space-time resolution because of lower true airspeeds.

(d) Mobility Support Aircraft: Cessna T207

A Cessna T207 (Fig. 5) was employed during the 1976 SSSP to act as a cargo support aircraft to the three research aircraft.

Fig. 5: Mobility Support Aircraft: Cessna T207

The Cessna T207 aircraft is the largest single-engine light plane manufactured in the U.S. and consequently it provides maximum volume and payload capabilities at minimum cost.



Since all three research aircraft had little or no room to carry supplies (magnetic tapes, maintenance kits, special lubricants, aircraft parts, etc.) and ground support personnel, the T207 was used to air lift these items to the staging area airports. From our field experience we now believe that the mobility support aircraft is an essential, if not critical, part of any type of surveillance program that requires the research aircraft to be in the field more than one or two days.

II. Measurements and Flight Profiles

The aircraft and instrumentation systems have been selected and/or designed to provide detailed wind, temperature, humidity, and pressure measurements in three separate severe storm regions. The measurements in these regions are needed to verify existing theories and/or help in the formulation of new physical-numerical cloud models.

A. Severe Storm Penetration Measurements: F101B

The aircraft storm penetration tracks usually consist of constant magnetic heading course lines in either crosswind or downwind directions. Essentially, a constant pressure altitude profile is flown outside the storm prior to cloud penetration. During the cloud penetration, a constant attitude profile is flown. From the initial point (I.P.) to the final point (F.P.) a single cloud penetration will normally take a minimum of 3-5 minutes. This profile will allow at least 10 miles of clear air measurements outside of the cloud from the I.P. and the F.P. to the visible cloud boundary. During these penetrations, the AADS-4A will measure and record the three-dimensional wind velocity, temperature, and pressure. The AADS-4A gyro-referenced platform provides aircraft reference data that is used to effectively eliminate errors in the atmospheric measurements due to aircraft roll, pitch, yaw, and accelerations. The complete system has been thoroughly calibrated and flight tested through intercomparison flights with NCAR aircraft and against instrument standards during tower fly-bys.

In general, the results from over 100 penetrations between 20,000 and 40,000 ft. MSL indicate a relatively smooth or non-turbulent environment at a distance 10 miles or more from the visible cloud boundary. Vertical velocities less than $\pm 1 \text{ msec}^{-1}$ are usually present in these regions. As the visible cloud boundary is approached, however, the vertical turbulent component

increases rapidly to $\pm 3-5 \text{ msec}^{-1}$. In addition, the penetration measurements of well-organized storms (Sinclair, 1973) indicate that there is, in the mean, a sheath of descending air surrounding the visible cloud boundaries. Within the visible storm boundaries, the vertical velocity of the air (with respect to ground coordinates) reaches peak values of $+ 40 \text{ msec}^{-1}$. Temperature anomalies of $+ 3^\circ\text{C}$ to $+ 10^\circ\text{C}$ usually accompany the large positive vertical velocity excursions. In addition, the horizontal gust velocities (i.e. for example $\Delta u_{a,g}$) appear to be slightly less than the vertical gust velocity component ($\Delta w_{a,g}$) i.e. the turbulent structure is anisotropic. These results are in general agreement with the data obtained by a similarly equipped F-100 aircraft of the NASA Langley Research Center (Steiner and Rhyne, 1962). The updraft region within the storm is of the order of 25 km in width and appears to be composed of a spectrum of eddy wavelengths which vary from 20 m to 2×10^4 m. Within the storm the turbulent energy appears to be separated into three distinct regions: (1) energy source region, (2) quasi-inertial subrange, and (3) an intermediate region where the steep spectral slope indicates rapid mixing with less buoyant air (Sinclair, 1974).

The in-cloud measurements are of interest to both NASA and CSU modeling and analysis groups.

1. Quantitative data is needed on the vertical motion and buoyancy fields within the severe storm to support the NASA satellite studies of severe storm growth and intensification modeling program on storm motion.

2. The measurements are required for internal consistency checks of the severe storm numerical model(s) now being developed at CSU. Because of the lack of a suitable mixing hypothesis or theory, there can be large variations in the shape and magnitude of the vertical motion profile with height in present-day models. Our current research (Sinclair, 1974) indicates that these in-cloud measurements will be extremely useful

in the formulation of a realistic mixing parameterization. This parameterization developed before cloud models will be able to specify a realistic mean and/or turbulent velocity field throughout the storm depth.

B. Sub-Cloud Measurements: T-28B

Depending on the visible cloud base, the sub-cloud measurements extend from the ground surface to approximately 15,000 ft. MSL. Higher level measurements are possible, however, since the N.A. T-28 has an operational ceiling of 30,000 ft. MSL. The flight patterns in the subcloud layer are essentially of two types:

- a. Continuous or semi-continuous box patterns at several altitudes are flown to obtain a quantitative picture of the horizontal wind field in the sub-cloud region. The instrumentation system and the flight profiles are designed such that an estimate of the circulation can be deduced from the wind measurements. In addition, these measurements can be used to calculate the convergent-divergent flow across the closed flight tracks and thereby provide an estimate of the mass, momentum, and heat transport near the cloud boundaries. This information is directly related to the storm development time, intensity, and duration.

- b. The sub-cloud flight program is also designed to systematically investigate and "map" the three-dimensional (kinematic-dynamic) structure of the sub-cloud layer. We have obtained these measurements in the past by flying three-dimensional tracks in the updraft as well as in the downdraft region from cloud base to the ground. These multiple-level plots of u , v , w , T , T_d , can be used to construct three-dimensional flow fields of the sub-cloud region.

Our previous experience in flying the sub-cloud updraft region(s) of severe storms and in the analysis of the data suggest the following

sub-cloud features:

a. The updraft region extends to the ground surface with a definite slope toward the direction of storm motion. The updraft is approximately 5-10 miles long and 1-2 miles wide. The most intense region is found in the vicinity of the so-called "scud cloud", and near but displaced below the storm cloud base. In many cases, however, this description can be severely distorted by the occurrence of multiple updraft regions which all appear to be feeding one central region of the storm above cloud base.

b. The temperature excesses in the updraft are usually only a few tenths of a degree centigrade and are many times negative indicating considerable mechanical forcing of the flow-field below cloud base. Regardless of the energy source (buoyancy and/or forcing), the cloud base mean vertical velocities are approximately $5-10 \text{ msec}^{-1}$ with maximum values of $15-20 \text{ msec}^{-1}$. Preliminary observations indicate that there may be significant entrainment into the updraft core from the precipitation core when the updraft and down-draft regions are in close proximity during the precipitation stage of the storm life cycle. This mixing may be responsible for the observed negative temperature excesses within the updraft near cloud base.

c. While the updraft region may appear "smooth" to the aircraft crew, the analysis of the turbulent velocity field shows a similar turbulent energy spectrum as that obtained at higher levels by the F101B penetration aircraft. Since the upper levels are definitely turbulent, the "smooth" nature of the sub-cloud updraft region may in many cases be a misnomer. In general, however, the picture, so far, clearly indicates that the cloud base updraft has less turbulent energy at low wavenumbers than that measured at medium or high levels in the storm. The sub-cloud updraft edges, on the other hand, can be as turbulent as the mid and/or upper cloud regions.

C. Mid-Level Storm Environmental Measurements: Q.A. B-80

The flight tracks for the mid-level storm environmental measurements are designed such that representative fields of temperature, pressure, humidity and winds are obtained from the visible cloud edge outward to approximately 25 miles upstream. The nominal flight altitude is approximately 15,000 MSL but may be modified in order to maintain clearance from the storm and/or to accomplish the most complete coverage of the wind field on a constant pressure surface. The measurement plan is designed to obtain the necessary modeling data for several scientific programs:

1. The NASA , SSSP personnel (Dr. W. Shenk) are interested in the mid-level temperature, moisture, and wind patterns upstream of the storm in order to investigate relationships between satellite measurements in this same region and storm growth and intensification.

2. NASA, Goddard (Dr. David LeVine): This is a piggyback experiment which is investigating the radio emission spectrum from severe storms. It is hypothesized that this spectrum may contain tornado cyclone signatures which will be useful in developing tornado forecasts. The SSMAG of Colorado State University has supported this program by providing the aircraft and personnel to assist the NASA representatives (Georgia Tech.) in the installation and flight operation phases of the program. The program is monitored by Dr. LeVine and will be reported more fully under a separate NASA report.

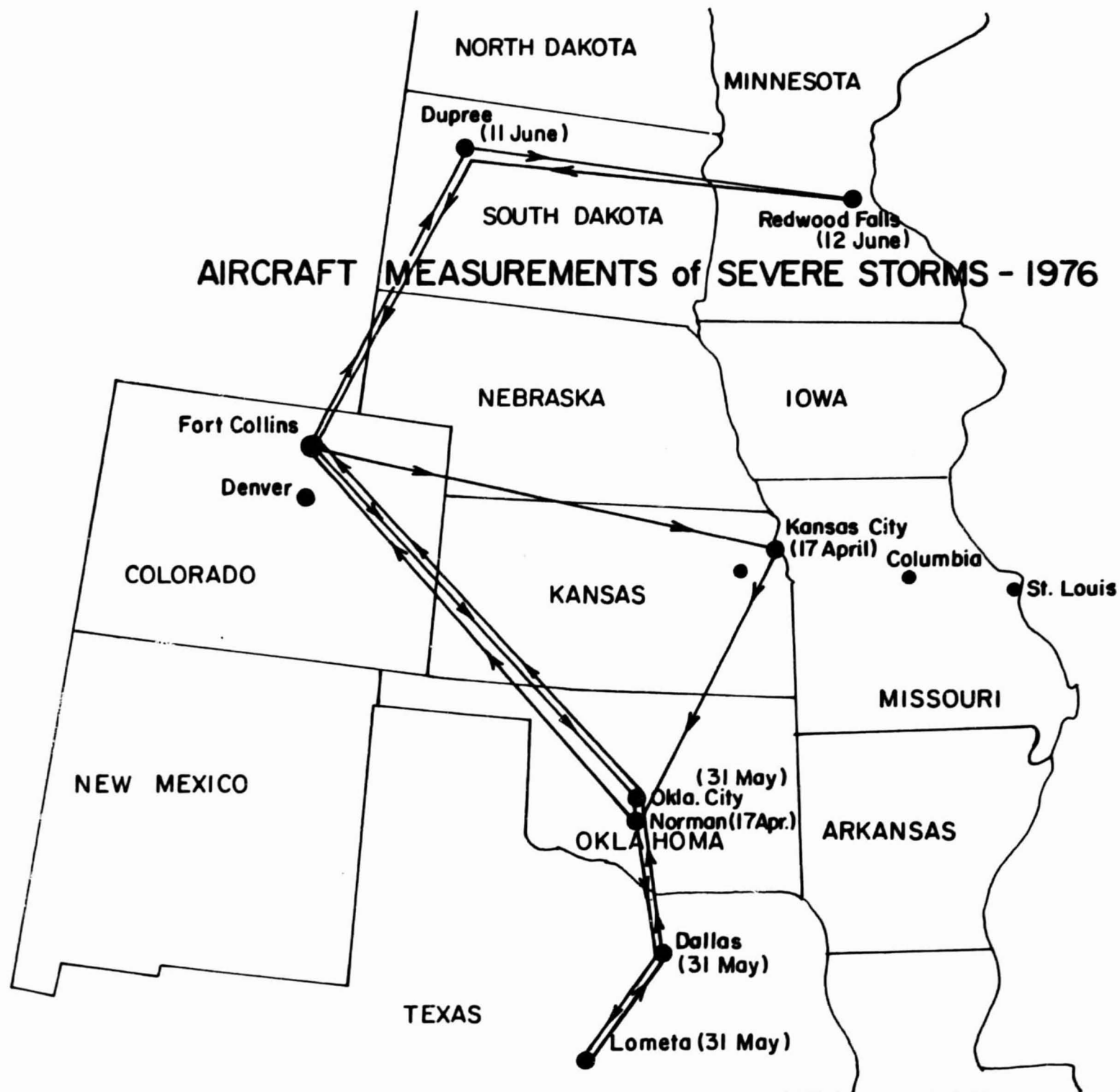
3. Colorado State University (Dr. P.C. Sinclair): The mid-level storm measurements are needed in the development of our severe storm entrainment-detrainment model(s). The environmental mean wind, and turbulent velocities, along with the temperature and humidity data, are of interest in our studies of the mass, momentum, and heat transfer across the storm boundaries. These transport components represent the

first step in the continuous horizontal mixing process that extends from the outer storm boundary to the center of the updraft core. The horizontal and vertical mixing not only controls the buoyancy of the updraft and hence the development of the storm, but it also acts as a connecting link between the strong horizontal flow of the environment and the intense updraft-downdraft region of the storm. The latter appears to be important with respect to the slope of the updraft axis and the storm's eventual decay.

III. Aircraft Deployment

Normally the SSSP Director would provide a 48 hr. alert for possible movement of the aircraft to an initial staging area. This 48 hr. alert was primarily for the purpose of flight preparation and field logistics planning for the specific area of operation. Because of the tenuous nature of the 48 hr. alert all aircraft were held at the home base. A second alert at 24 hrs. prior to anticipated activity was used to move the aircraft and crews to the best forward staging area. Because of aircraft weight restrictions due to instrumentation load and on-board flight crews, ground support personnel and equipment were moved to the selected staging area by a special mobility support aircraft (Fig. 5). After arrival at this initial staging area, the aircraft could in some cases be repositioned for more optimum locations for the anticipated storm flights. The 1976 SSSP staging areas and enroute tracks of each storm case are shown in Fig. 6. These alerting procedures, as originally envisioned, were well thought out and appeared to present no anticipated problems. However, the decision to move at the 24 hr. alert time should be modified to allow more time for aircraft, crew and logistics support. In several cases the alert came late in the day and the decision to move the following morning meant that the storm flights were made on the same day as the aircraft staging day. This resulted in flight crews exceeding authorized daily flight hour limits and missing meals (lunches). Also, the arrival back at the final staging base after 2000 LST, meant that crew rest would be insufficient for scheduling a second storm flight day. Several easily incorporated improvements in the present alert plans and communication-vectoring procedures for future programs are discussed in the Summary and Conclusions, Section V. In general, however, we feel that our experience from this second operational year has shown that the initial mobility concept is valid and can

Fig. 6: Location of Aircraft Staging and Deployment
Points and Research Measurement Areas.



be fully exploited to provide the necessary severe storm data that fixed location programs cannot provide in a reasonable time limit.

The daily status of the flight measurement program is outlined in Table I. On 1 March 1976 the NASA funding for the CSU program in the SSSP was received. In approximately 3 weeks, two research aircraft (Q.A. and T-28) and the mobility support aircraft (T207) were prepared and in a ready status. The significant weather, crew and aircraft status, and deployment alerts are documented for each day during the field measurement program: 25 March - 16 June (Table I).

TABLE I: DAILY STATUS OF FLIGHT MEASUREMENT PROGRAM

<u>Date</u>	<u>Storm Alert Status</u>	<u>Meteorological Situation</u>	<u>Remarks</u>
1 Mar. 1976			NASA funding received at CSU
25 Mar. 1976	Alert Notice (NASA) for 26 Mar. received at 1000 MDT - later cancelled.	No significant severe storm weather systems in research area.	Field program start date
26 Mar. - 12 Apr.	Stand-by aircraft and crews	No significant severe storm weather systems in research area.	Performing research aircraft maintenance and instrumentation calibration flights with NCAR.
13 Apr.	Alert Notice (NASA) for 15 April.	No significant severe storm weather systems in research area.	Final aircraft and instrumentation checks
14 Apr.	Alert Notice (NASA) for 15 April.	Severe storms expected in Oklahoma tomorrow	Load aircraft with fuel and crew equipment and provisions.
15 Apr.	Queen Air (Q.A.) research aircraft departs Fort Collins, CO for Kansas City at 1206 MDT.	Frontal system to east of Colo. with intense severe storms from Minn. to Texas.	RON Kansas City. Expect move south to Oklahoma area tomorrow. 36 tornadoes and 37 severe storms in U.S. T-28 and F101B aircraft down with engine and radio problems.
16 Apr.	Depart Kansas City @ 1135 CST - arr. Norman, Oklahoma @ 1425 CST.	Frontal passage K.C. @ 0800 CST. Satellite pictures show moisture flux into Oklahoma.	RON Norman, Oklahoma. No NASA calls. Informed Ed Ferguson at Kansas City Severe Storm Forecast Center (SSFC) of our location and status.
17 Apr. - Sat.	NASA Learns arrive, discuss weather situation with Shenk and Pearl at NSSL. Depart Norman @ 1141 CST for Salina, KS.	Cold-warm front wave over N. Oklahoma. 4-5 severe storm cells NNE of Norman.	Kansas City SSFC called off research at 1225 CST because cells were not developing - Tops ~20,000'. Land Oklahoma City @ 1314 CST.

18 Apr. - Sun.	Return to Fort Collins Alert Notice terminated	High pressure ridge dominates central U.S. with no signifi- cant severe weather forecast.	
19 Apr.	Stand-by aircraft and crews	No significant severe storm weather.	Aircraft maintenance and in- strumentation check out.
20 Apr.	Stand-by aircraft and crews, no alert notice.	No significant severe storm systems in research area.	Prepare T-28 and F101B aircraft for tower fly by calibrations.
21 Apr.	Stand-by aircraft and crews, no alert notice.	No significant severe storm systems in research area.	T-28 engine maintenance, 7 tornadoes in U.S.
22 Apr.	Alert Notice for 24 Apr.	Cold front through Fort Collins by afternoon.	T-28 engine maintenance, 5 tornadoes in U.S.
23 Apr.	Alert Notice for 25 Apr.	Cold front moving through Colorado.	Expect T/O tomorrow to follow cold frontal system eastward. 10 tornadoes in U.S.
24 Apr. - Sat.	Alert cancelled (NASA). New Alert Notice for 26 Apr.	Cold frontal system moving slowly eastward with good activity - too late to chase with aircraft now.	19 tornadoes in U.S.
25 Apr. - Sun.	Alert cancelled (NASA) for 26 Apr. Next alert on 29 Apr.	No significant severe storm systems in research area.	3 tornadoes in U.S.
26 Apr.	Stand-by aircraft and crews.	Deep low pressure system over Great Basin with upslope along front range. Rain, sleet, hail during day in Ft. Collins.	T-28 test flight cancelled be- cause of low ceilings (<500ft.) and vis. <1 mile. 5 tornadoes in U.S.
27 Apr.	Stand-by aircraft and crews.	Low in Great Basin with up- slope along foothills. 2"- 4" snow in Fort Collins this morning.	Test flights cancelled because of weather.

28 Apr.	Stand-by aircraft and crews.	Great Basin low-center moving into Okla. Upslope weakening with 7,000' bases by afternoon in Fort Collins.	T-28 test flights on new engine.
29 Apr. - 22 May - Sat.	Stand-by aircraft and crews.	No significant severe storm systems in research area.	Aircraft maintenance, calibration and test flights.
23 May - Sun.	Crew rest day	No significant severe storm systems in research area. Low ceilings & heavy rain in Colo. & Neb.: 5-8"/hr.	10 tornadoes in U.S.
24 May	No alert	Excellent severe storm weather in research area.	Buckley ANG Base runway closed until 27 May - delays planned. F101B tower fly-by calibration flights. 10 tornadoes in U.S.
25 May	Alert Notice (NASA) for 27th & 28th	Excellent severe storm weather in research area.	T-28 instrumentation maintenance.
26 May	Alert cancelled (NASA)	All severe storm activity moving eastward out of range.	Prepare F101B for tower fly-by calibrations.
27 May	Stand-by aircraft and crews.	No significant severe storm systems in research area.	F101B tower fly-by calibrations.
28 May	Stand-by aircraft and crews	No significant severe storm systems in research area.	F101B tower fly-by calibrations.
29 May	Crew rest day. Alert for 31 May.	No significant severe storm systems in research area.	F101B tower fly-by calibrations.
30 May	Alert for 31 May	Frontal system and wave pattern in Texas.	All personnel preparing aircraft for deployment tomorrow.

31 May	3 aircraft depart Colo. for first staying point at Okla. City.	Frontal system and wave pattern in Texas. SSFC expects good severe storm activity in wave pattern area.	F101B grounded because of electronic problems. Queen Air returned from research area due to electrical power (alternator) problems.
1 June	Alert cancelled (NASA). All aircraft returned to Fort Collins.	All severe storm activity moved eastward out of research area.	Queen Air alternator-battery problem repaired in Okla. City by Aircraftsman Inc.
2 June	Stand-by aircraft and crews.	All severe storm activity moved eastward out of research area.	F101B returned to flight status.
3 June	Stand-by aircraft and crews.	No significant severe storm systems in research area.	Installing Dr. Wilson's lightning research equipment in Queen Air. This is a piggy-back experiment from Georgia Tech., supported by NASA.
4 - 8 June	No Alert Notices.	Some severe storm activity in Denver area with 5 tornadoes in Colo.	22 tornadoes in U.S.
9 June	Alert Notice for 11 June.	High pressure dominates research area-weakening however.	Prepare aircraft and crews for deployment.
10 June	All aircraft depart Fort Collins before noon for Pierre, S.D. F101B will use Rapid City or Fargo.	Front to west moving into S.D. and bringing severe storm activity.	F101B aborted mission due to radio (VHF) communication problems.
11 June	Queen Air and T-28 flew extensive research missions on storm cells NW of Dupree S.D.	Line of severe weather did form in central S.D. as forecast by Kansas City & SELS.	Queen Air and T-28 returned to Pierre, S.D. Lears landed Great Falls, Mont.
12 June - Sat.	Queen Air and T-28 depart Pierre, S.D., arr. Minn., Minn. @ 1200 CST. Lears arr. 1330 CST & Q.A. & T-28 depart for research area near Redwood Falls @ 1430 CST.	Line of severe weather moving eastward and intensifying.	F101B returned to flight status-test flights today.

13 June - Sun.	No Alert Notice. All aircraft return to Colo.	Line of severe weather moved further east out of research area. K.C. forecast severe storm activity in S. central Neb. & Okla. panhandle on 14th & 15th - suggest Ft. Collins as staging point.	Unable to contact NASA for possible Alerts next week. All aircraft in flight status.
14 June	No Alert Notice. Stand-by aircraft and crews.	Strong cold frontal passage with associated severe weather.	Unable to contact NASA for possible Alerts this week. All aircraft in flight status.
15 June	Stand-by aircraft and crews.	No significant severe storm weather systems in research area.	Dr. Wilson removed his research equipment from Q.A. Proceeding with initial data checks and analysis.
16 June	End of Flight Measurement Phase of Severe Storm Research		

IV. Severe Storm Cases

A. 17 April: Norman, Okla. Case

A cold frontal system which had moved through Colorado earlier was positioned to the east of the State with intense weather expected along its N-S boundary from Minnesota to Texas. The Queen Air (Q.A.) research aircraft departed Fort Collins-Loveland Airport at 1206 MDT (15 April) for Kansas City. The plan was to wait on the ground for the frontal passage at Kansas City and then follow the severe weather eastward using the relatively clear western boundary of the front for all approaches and departures from the severe storm cells. However, a Kansas City frontal passage at 0800 CDT (16 April) resulted in dry subsidence behind the front with no severe weather in the area. Consequently, the Q.A. and T-28 were directed southward toward a better moisture source in Okla. Both aircraft arrived Norman, Okla. at 1425 CST ready for severe storm research flights. NASA Learjets did not arrive until the next day (17 April). The synoptic situation on the 17th had a cold front with warm front wave centered over northern Okla. with the cold front extending south through Texas. Satellite pictures showed 4-5 severe storm cells NNE of Norman in Kansas - this area was selected for the aircraft measurements. The Q.A. and T-28 took off at 1141 CDT for Salina, Kansas, but the cells failed to develop (tops only 20,000 ft) sufficiently and therefore the mission was cancelled by the Kansas City, Severe Storm Forecast Center. Consequently, no aircraft measurements of severe storms were obtained during this first attempt of the 1976 field experiment. It was constructive however, in indicating to everyone the importance of maintaining frequent communications between the primary field and forecasting groups.

B. 31 May: Lometa, Texas Storm Case

1. Synoptic Weather Situation

A cold frontal system in the midwest extended southward through southeastern Oklahoma and central Texas (Fig. 7). Ahead of the cold front, strong advection of warm, moist air from the south was taking place. Behind the front to the west the air was warm and dry, creating a large moisture and stability contrast across the frontal zone. The surface front was supported by a rather weak trough circulation aloft as shown on the 0000Z (1 June) 500 mb chart (Fig. 8). Severe storms formed early in the afternoon generally ahead of the cold front and continued to increase in intensity with tops over 60,000 ft. by late afternoon - early evening as shown on the Radar Chart of 1 June 1976 (0235Z), Fig. 9.

2. Research Aircraft Deployment

The CSU Q.A., T-28, and TC207 (support aircraft) left Fort Collins at 0640 MDT for Oklahoma, City. On landing, we were informed by NASA to proceed directly to Dallas, Texas for staging to the research area estimated to be 200 nm west southwest near Abilene, Texas. The Q.A. and T-28 arrived Dallas at 1245 CDT and waited for the NASA Learjets which arrived between 1315-1330 CDT. The Q.A. and T-28 departed Dallas at 1430 CDT enroute to the research area near Lometa, Texas where a line of numerous cells was developing (Fig. 10). The T-28 obtained excellent inflow-outflow data at cloud base. The Q.A. however, had electrical power problems (Ni-cad battery and alternator malfunction) after reaching altitude (15,000 ft) and returned to Dallas.

3. Aircraft Measurements (T-28 research aircraft)

The cloud base airflow measurements by the T-28 aircraft reveal in detail several severe storm circulation features that have not been documented previously by aircraft measurements:

- (a) Flight track #1 was designed to probe the eastern flank

Fig. 7: 1 June 1976, 0000Z Surface Chart

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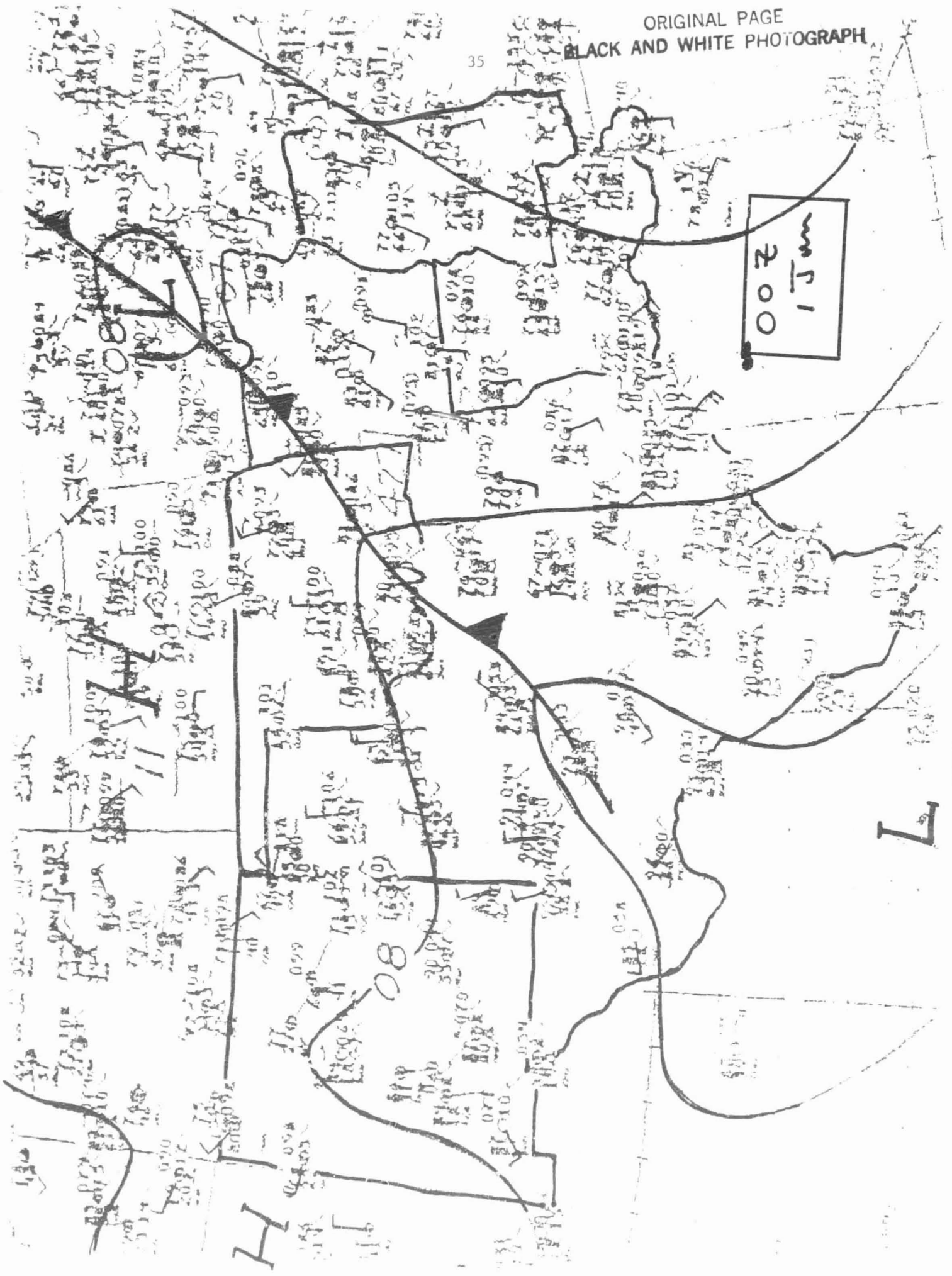


Fig. 8: 1 June 1976, 0000Z 500 mb Upper Air Chart

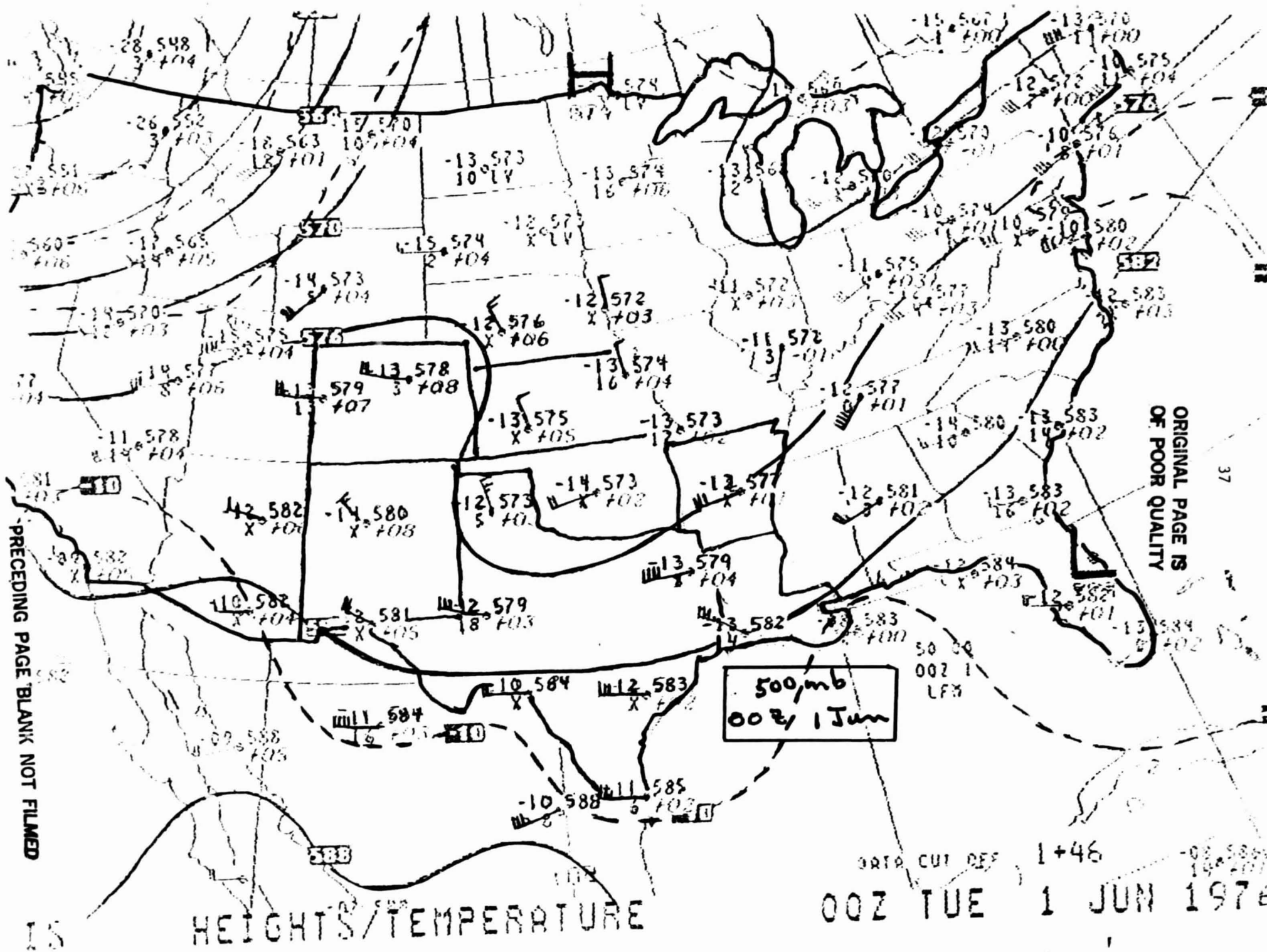


Fig. 9: 1 June 1976, 0235Z Radar Summary Chart

Fig. 10: Developing line of cells near Lometa, Texas:
31 May Storm Case.



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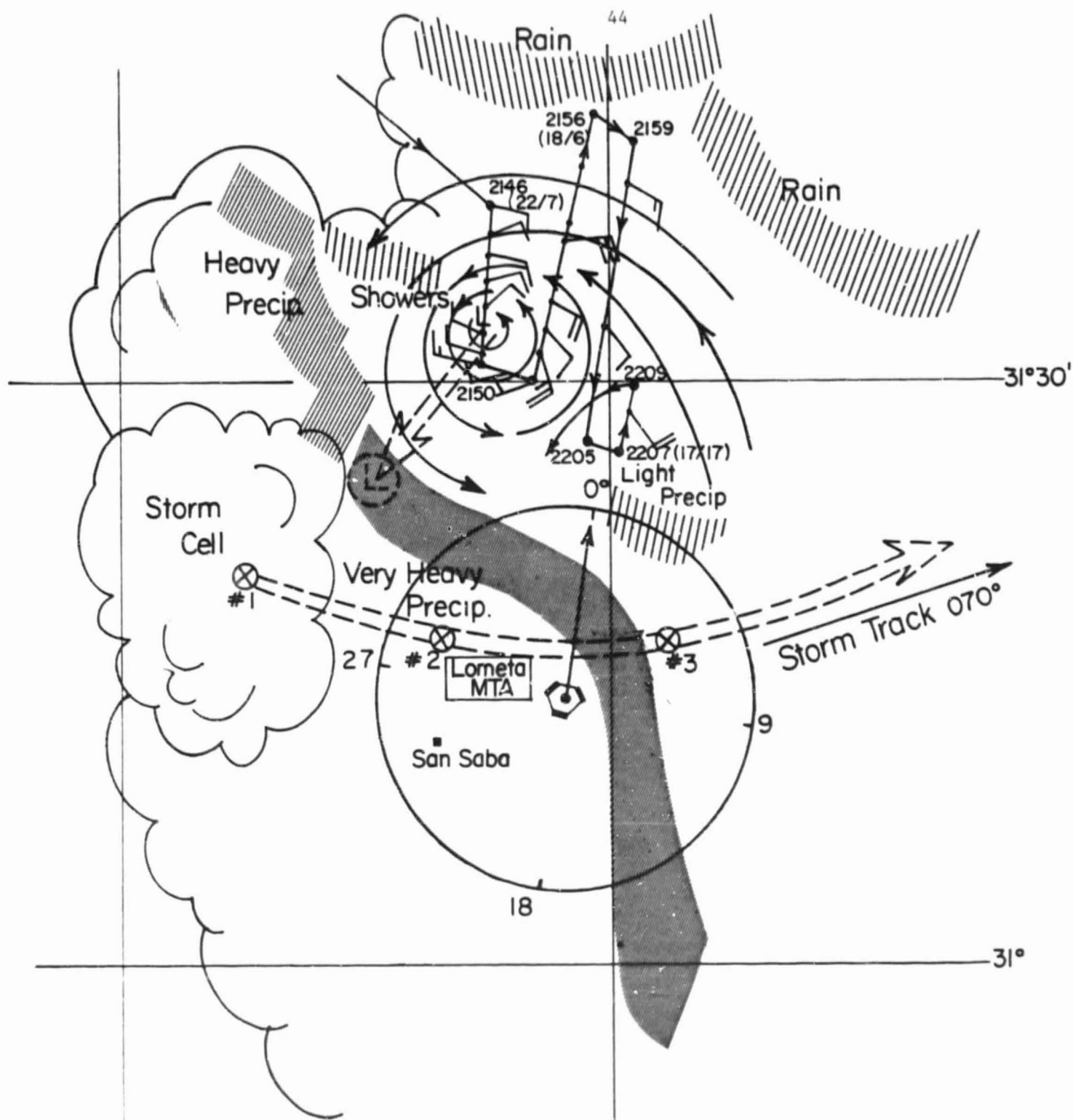
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of the severe storm cell #1 (Fig. 11) in order to locate the inflow and updraft regions. However, at the time the measurements appeared very chaotic and suggested outflow rather than inflow. Subsequent analysis of the data revealed, however, that the aircraft had made repeated penetrations of a small cyclonic vortex below cloud base. Cloud base was nominally 7,000 ft. MSL with lower (scattered) cumulus and scud clouds bases at 4,000 ft. MSL. The T-28 flight altitude was at $5,000 \pm 300$ ft. MSL over terrain with a mean elevation of approximately 1000 ft. MSL. During the penetration of the vortex core (2146Z - 2150Z) there was generally weak subsidence (0.5 - 1.0 m sec⁻¹) which may account for the weak winds within the vortex (i.e. at $r < 3$ -4 nm). The vortex was separated from the storm cell main updraft by a band of very heavy precipitation.

(b) During approximately the next two hours, the storm cell moved from position #1 to position #2, ($098^\circ/19$ knts) and then to position #3 ($091^\circ/19$ knts) (Fig. 11). While the cell was at position #2, the storm outflow on the NE quadrant was measured from 2218Z-2323Z; and at position #3, the storm inflow in the storm cell NW quadrant was measured between 2333Z-2406Z (Fig. 12). The data from both Flight Tracks #2 and #3 were plotted and analysed to correspond to a mean time of approximately 2321Z in order to show the interaction of the outflow with the inflow and the probable location of the vortex center. The positions of the cyclonic vortex center (Fig. 11) indicates a movement from $338^\circ/20$ nm to $305^\circ/14.5$ nm (MTA VOR coordinates) in approximately 30 minutes. The actual motion, although shown as rectilinear, may have been slightly longer if steered by the ambient flow along a curved cyclonic path. The

Fig. 11: Lometa, Texas Storm Case: 31 May 1976, T-28
Flight Track #1.

This was a back-feeder type storm with a small vortex located to the north of the heavy precipitation band of the storm cell (#1). The wind is in knots (ground reference), the temperature and dew point ($^{\circ}\text{C}$) are indicated below the time (z) as (T/ T_d). The movement of the cyclonic vortex between Flight Tracks #1 and #2-#3 (Figs. 11 & 12) is shown by the arrow pointing to the S.W. The storm cell successive positions from 2146Z to 2406Z are labeled #1, #2, and #3 which represent a storm track trajectory directly across the Lometa VORTAC.



Lometa, Texas Storm Case

T 28 Flight Track #1

31 May 1976

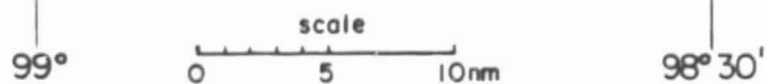
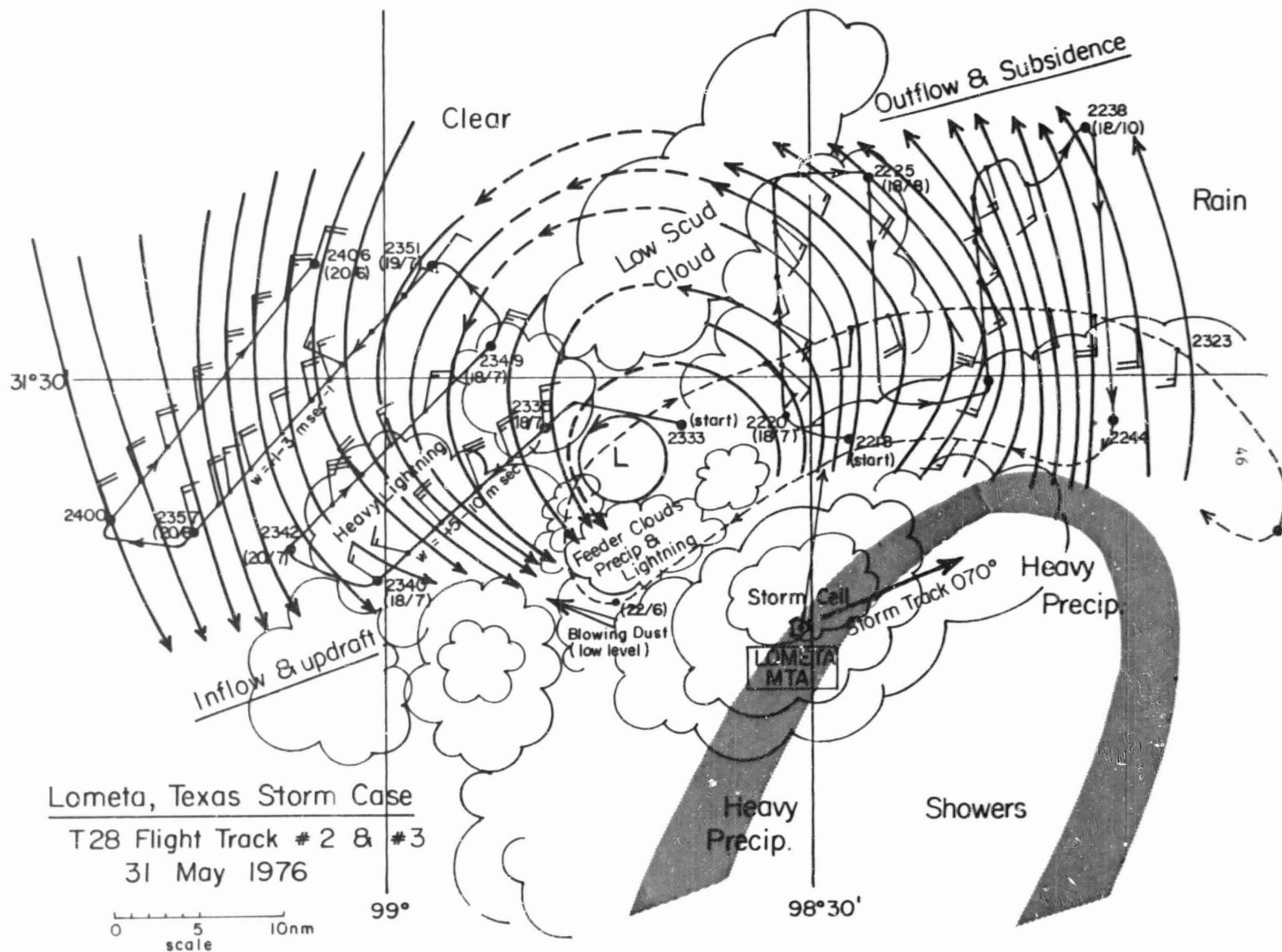


Fig. 12: Lometa, Texas Storm Case: 31 May 1976
T-28 Flight Tracks #2 and #3

The symbols are the same as in Fig. 11 with the added vertical motion indicated by $\pm w$ along the constant heading flight tracks.



Lometa, Texas Storm Case
 T28 Flight Track # 2 & #3
 31 May 1976

center of the cyclonic rotation some 30 minutes later was well-established by the wind analysis obtained along Flight Tracks #2 and #3 (Fig. 12). Although the center of the vortex circulation has moved southward toward the feeder clouds of the storm cell, it still remained just outside (north) of the main inflow-updraft region. This analysis shows quite clearly that the storm is a back-feeder with outflow and subsidence in the left front quadrant and inflow with strong updrafts in the left rear quadrant. This appears to be in agreement with our previous squall line aircraft measurements in Oklahoma where the strong (squall-line) updraft is nearly always found on the backside (westside) of the individual storm cells. Thus, the downdraft outflow air recirculates around the northern boundaries of the storm to the backside where it may enter the inflow-updraft circulation. Note that in this case, the temperature and moisture content of the downdraft-outflow air is only slightly cooler ($1-2^{\circ}\text{C}$) and more moist than the unmixed inflow-updraft air entering the storm on the west side. It is of interest to note that this inflow-outflow, updraft-downdraft configuration is almost exactly opposite to that found in most northeastern Colorado storms which are usually front-feeders. The inflow on the cell backside increased in vertical velocity from $1-3 \text{ m sec}^{-1}$ to $5-10 \text{ m sec}^{-1}$ as the edge of the main storm cell was approached. The heavy precipitation band shown in Fig. 12 represents the downdraft region of the storm cell. The low-level outflow from this precipitation downdraft is in the opposite direction to the west side inflow. It was easily visible to the flight crew by the blowing dust near the ground as well as by the wall of dust lifted up to flight level by the updraft core (Fig. 12). This vertical recirculation of the

precipitation-core air back into the updraft has also been observed many times in Colorado front-feeder storms. This particular storm cell was electrically very active with approximately 12 cloud-to-ground lightning strikes per min. Also, the NASA Learjets which were studying the same cell at high altitude reported overshooting tops to 55,000 ft. and jumping cirrus.

C. 11 June: Dupree, S.D. Storm Case

1. Synoptic Weather Situation

On 10 June, NASA informed us that the frontal system in eastern Montana and Wyoming was expected to move into central South Dakota with severe weather running ahead of the cold front. The surface chart for 0000Z on 12 June located a stationary front extending to the north and south of a low pressure center in central South Dakota (Fig. 13). Ahead of the front, the surface temperatures in South Dakota were generally 90°-100°F (Pierre, S.D., 100°-110°F) with dew points 60°-70°F. This warm, moist boundary layer developed from the northward movement of Gulf air by the subtropical high pressure circulation center in the southeast U.S. Behind the front, surface temperatures and dew points were significantly cooler, (60°-70°F) and (40°-50°F) respectively. At the upper levels, a moderately deep trough and vorticity center was centered over extreme southwestern Wyoming and southern Idaho which was producing strong southerly flow over central South Dakota (Fig. 14). The severe storm locations as depicted by radar are shown in Fig. 15 for the period approximately 3-4 hours after the aircraft measurements were completed in central South Dakota. By this time (0435Z), the severe storm cells investigated by the aircraft in west, central South Dakota had moved north eastward to a more central position in the State.

Fig. 13: 12 June 1976, 0000Z Surface Chart

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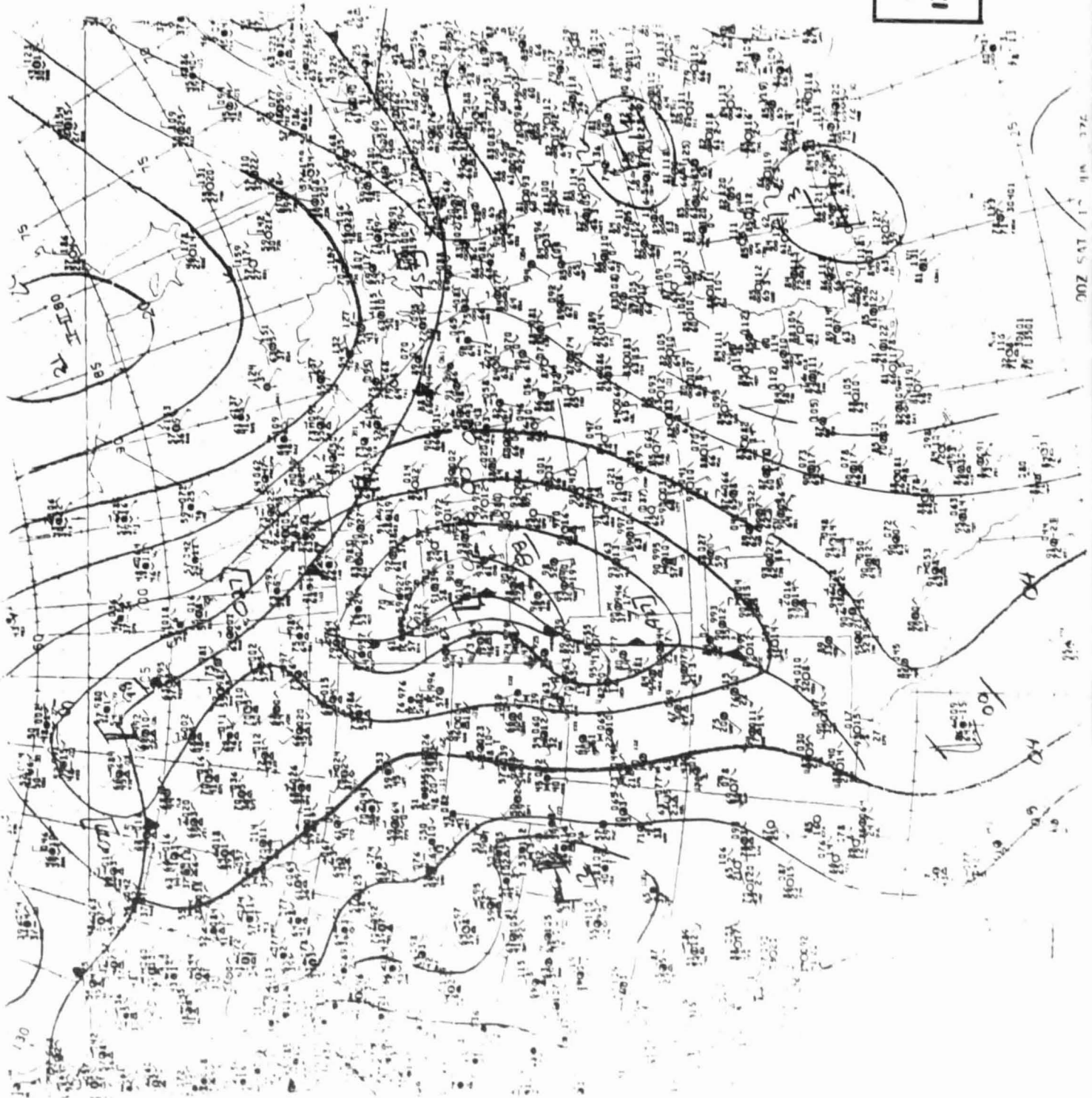
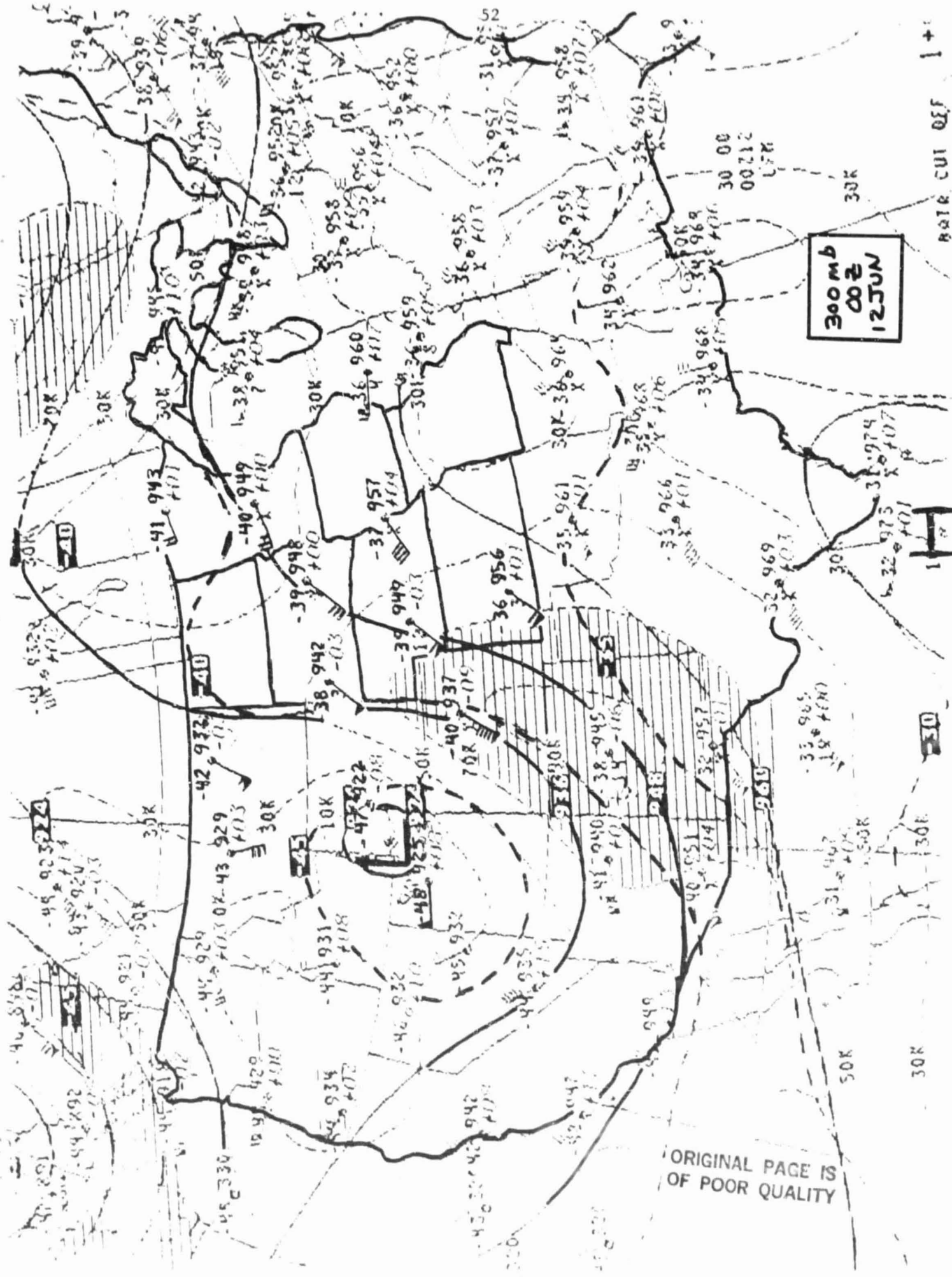


Fig. 14: 12 June 1976, 0000Z 300 mb Upper Air Chart



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Fig. 15: 12 June 1976, 0435Z Radar Summary Chart

2. Aircraft Deployment

On the morning (1120 MDT) of 10 June, three aircraft (Q.A., T-28, T207) departed Fort Collins, Colorado for the primary staging base at Pierre, South Dakota. All aircraft arrived at Pierre, S.D. by 1450 MDT. The F101B was scheduled for a storm flight departure from Buckley ANG Base with a recovery at Rapid City, South Dakota. On arrival at Pierre, S.D., we contacted Kansas City SSFC for a severe weather up-date. Ed Ferguson's office had no NASA messages and agreed that our present location was the most logical one for storm flights the next day. NASA (Ed Pearl) contacted us at 2200 MDT and confirmed this staging area selection. On 11 June the Q.A. and T-28 research aircraft departed Pierre, S.D. at 2200Z and obtained excellent measurements at cloud base and at mid-levels behind a line of several moderately intense cells located northwest of Dupree, S.D. (Fig. 16). After the measurement period (2200Z-0138Z), the Q.A. and T-28 research aircraft returned to Pierre, S.D. with the NASA Learjets landing at Great Fall, Montana. The F101B aircraft experienced radio (VHF) communication problems and aborted the mission.

3. Cloud Base Measurements: T-28 Research Aircraft

The T-28 conducted a series of four (4) separate flight tracks designed to investigate the inflow-updraft region of the most intense cell in the line NW of Dupree VOR (Figs. 17-19). Several important features of these measurements and the flight crew observations are outlined below:

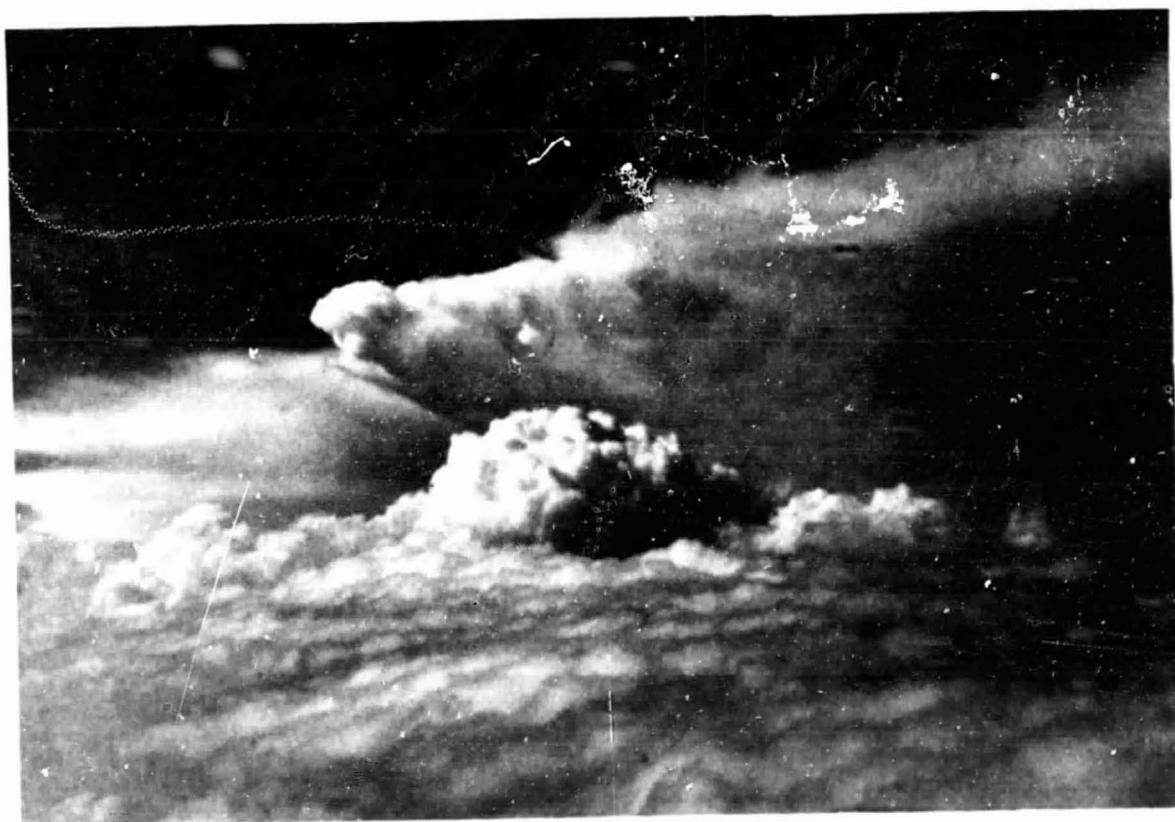
(a) In agreement with all of our previous sub-cloud, inflow measurements, strong inflow and updrafts are located along the leading edge of the seed cloud that forms slightly below the main cloud base. As this region is approached, the vertical motion

Fig. 16: View of squall line cells from Queen Air
research aircraft

Picture #1 depicts the south end of the squall line while #2 shows the line of cells to the right of the Q.A. aircraft which is now on the back side of the line at an altitude of approximately 16,000 ft. MSL. Note the shelf of cumulus below the aircraft and the westward extent of the cirrus anvils to the north.



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Fig. 17 - 19: Dupree, South Dakota Storm Case:
11 June 1976, T-28 Flight Tracks #1-#3.

The symbols are the same as in Figs.
11 & 12.

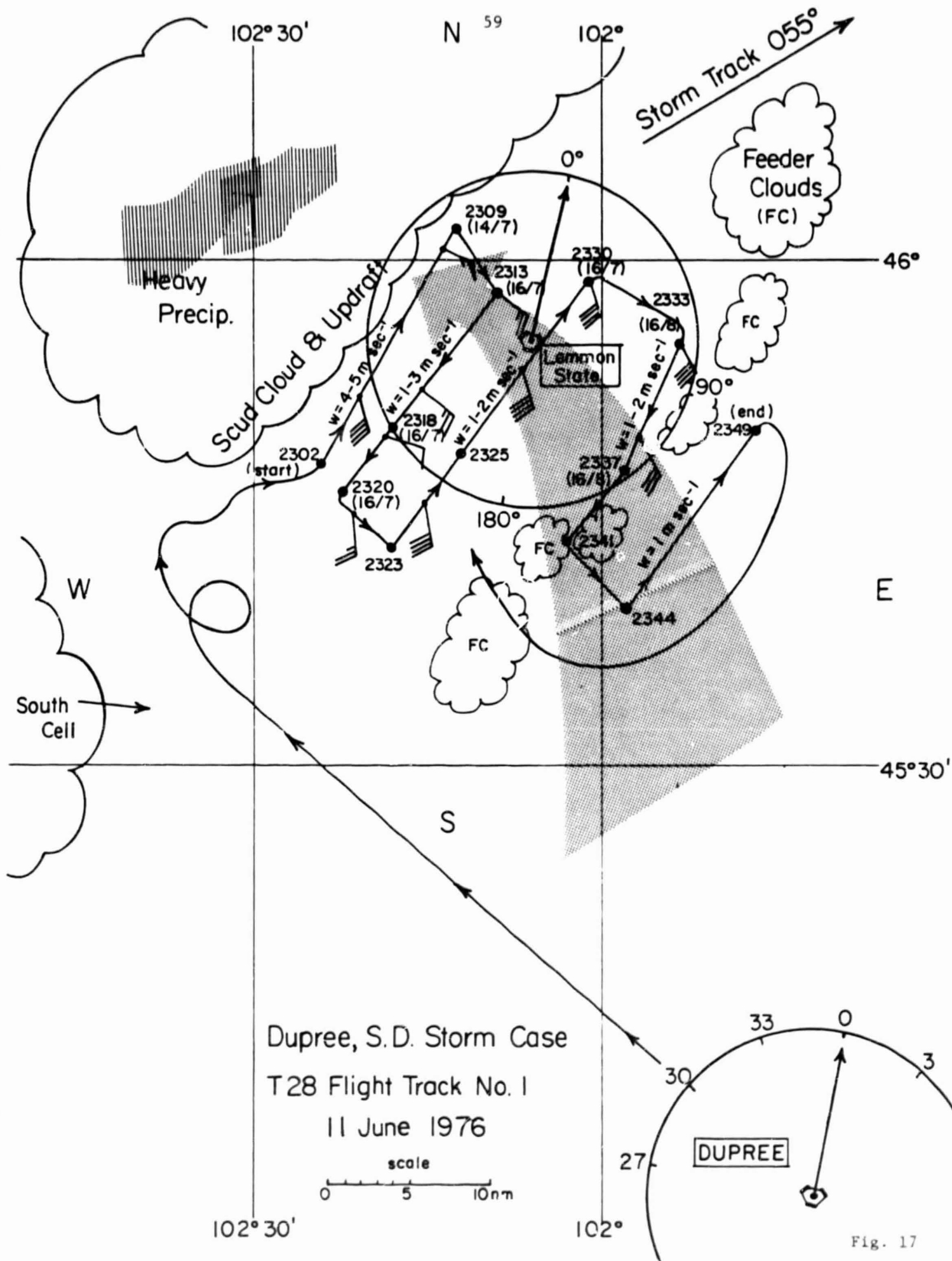
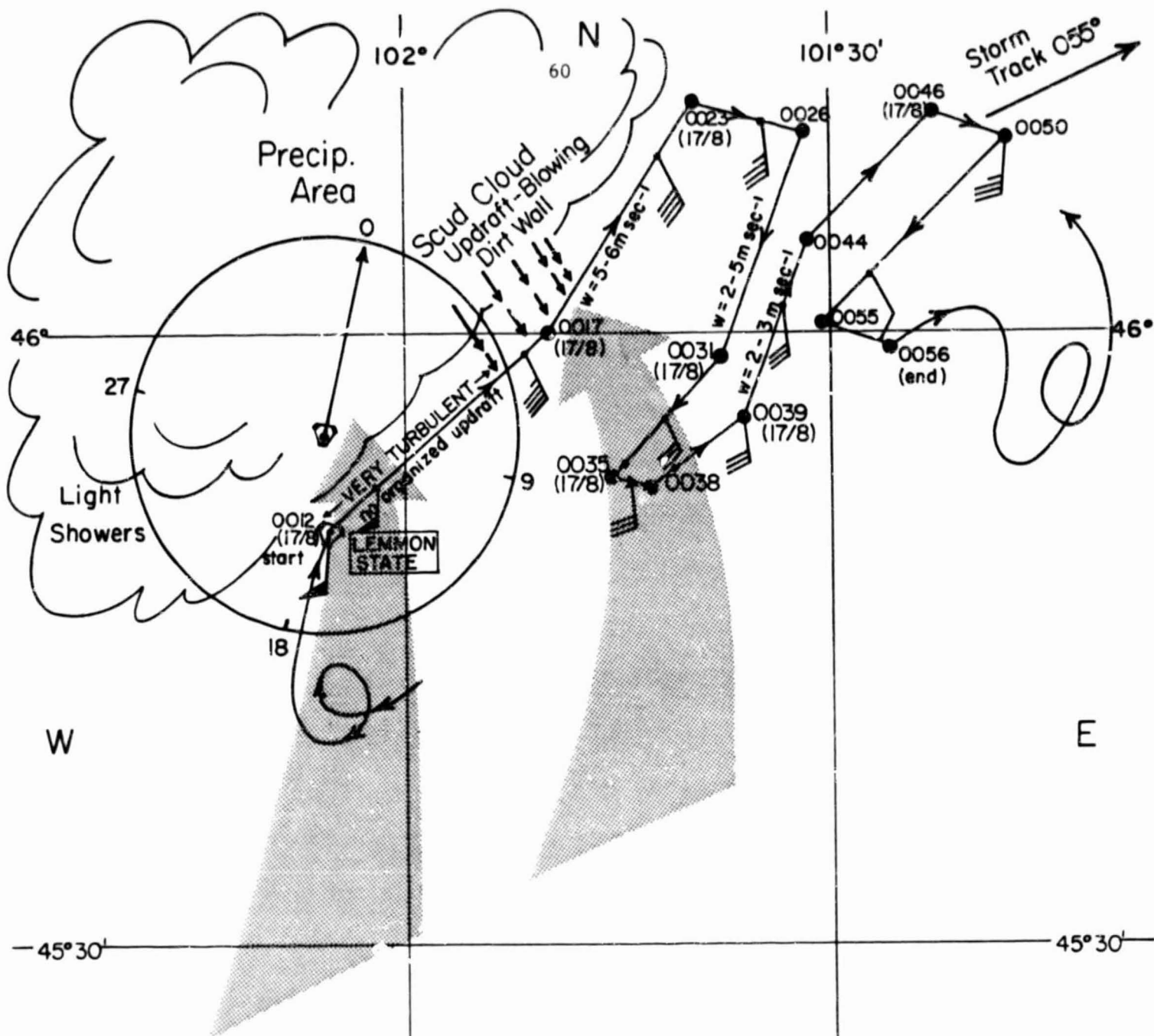


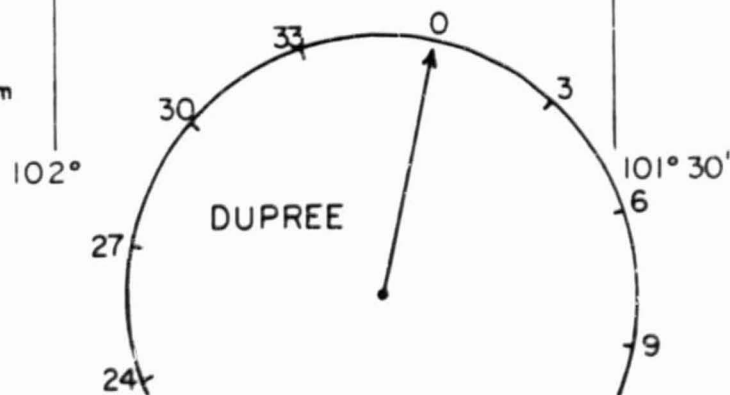
Fig. 17

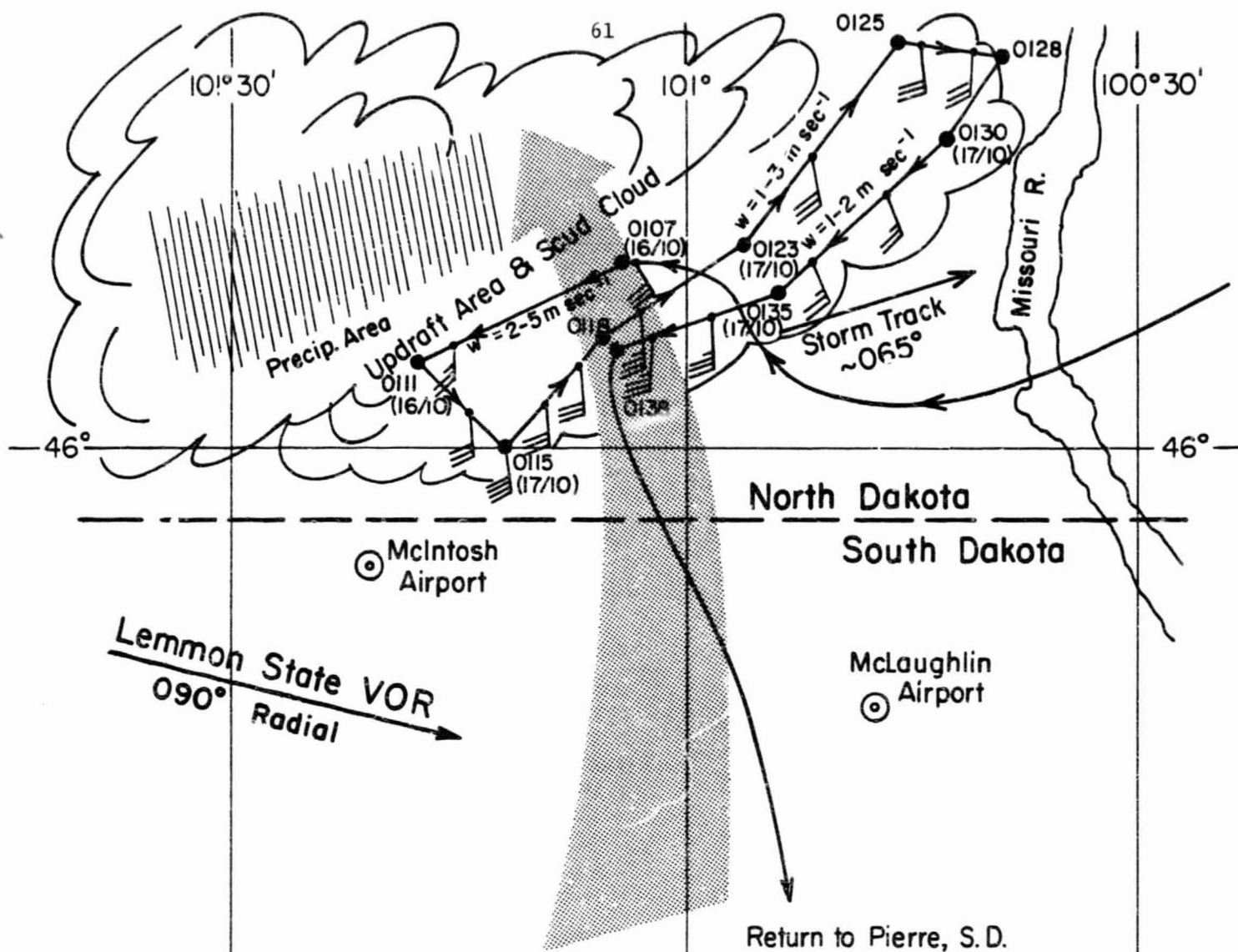


Dupree S. D. Storm Case

T 28 Flight Track No. 2
11 June 1976

scale
0 5 10nm





Tracked Cell from 20 n.m. SW Lemmon State
to 75 n.m. NE Lemmon State VOR

Dupree S.D. Storm Case

T 28 Flight Track No. 3
JUNE 1976

scale
0 5 10 nm

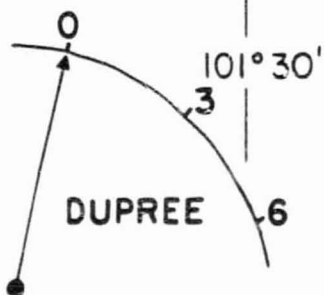


Fig. 19

increases from approximately 1 msec^{-1} (20 nm) to $5\text{-}10 \text{ msec}^{-1}$ directly in front of and underneath the scud cloud.

(b) Also, in agreement with many of our previous severe storm measurements at cloud base, we have observed the recirculation of the downdraft air (in the precipitation core) lift significant quantities of dirt from the ground into the main updraft of the storm cell (Fig. 18). A similar wall of dirt also was observed to meet the updraft core near the surface in the Lometa, Texas Storm Case (Fig. 12). Note that the downdraft air of the precipitation core spreads out at the ground and produces a high-velocity counter flow to the inflow region at low levels. The convergence zone formed by these two opposing flows can have a controlling effect on the position of the updraft as well as the moisture flux into the updraft core.

(c) Along the entire line of cells, the inflow and updraft were located on the east side, i.e. the cells would be classified as front feeders in contrast, for example, to the Lometa, Texas storm case (31 May). Also on the east side, significant cloud-to-ground lightning was observed to the west in the vicinity of the precipitation core.

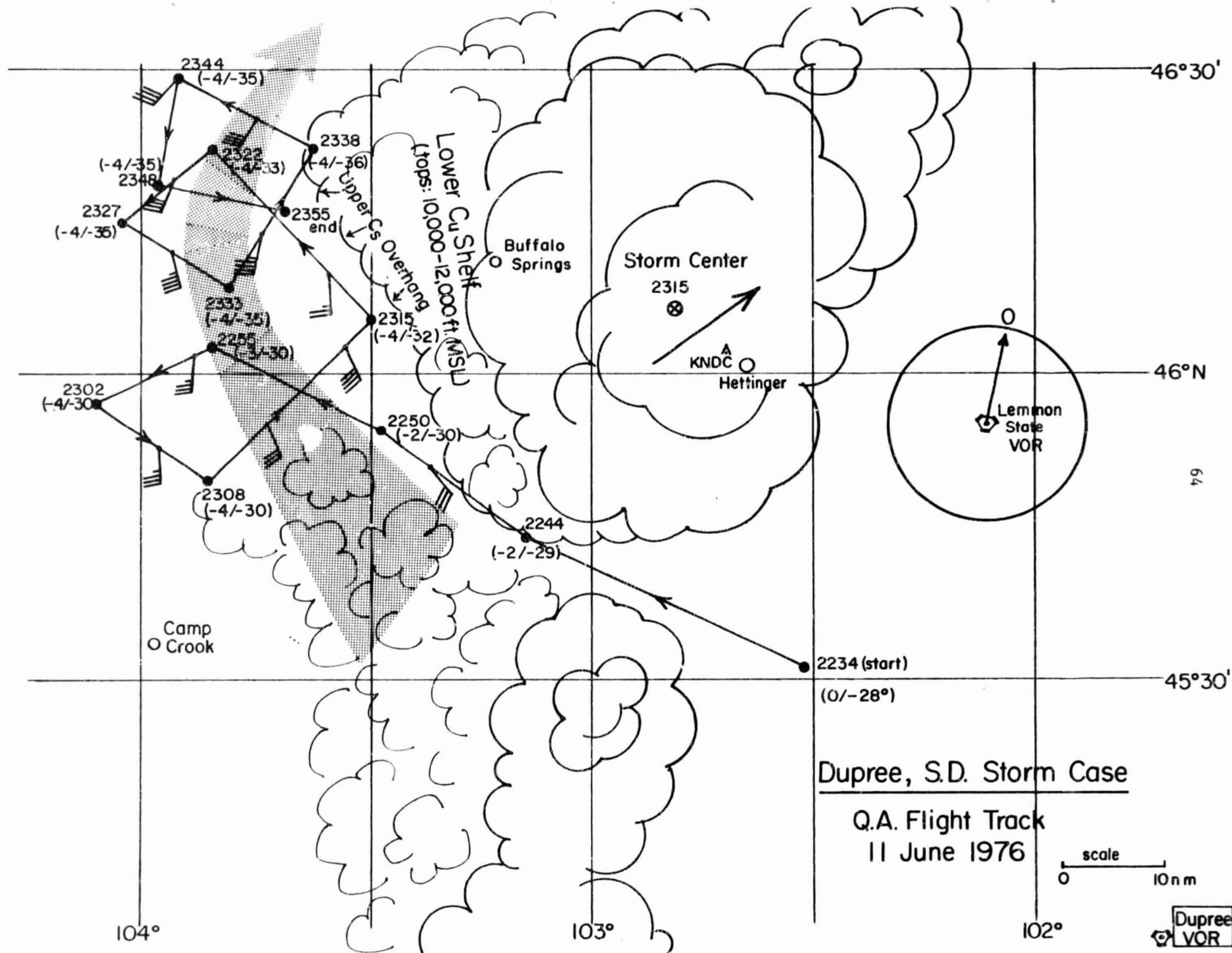
4. Mid-Level (15,000 ft. MSL) Measurements: Queen Air Research Aircraft

The Queen Air (Q.A.) research aircraft was directed to the west side of the most intense part of the squall line by the upper level Learjet aircraft. Successive closed circuits were flown by the Q.A. to obtain wind, temperature, and moisture data in the clear air at mid-levels to the rear of the storm system (Fig. 20). The data analysis indicates:

(a) The flow tends to follow the general boundaries of the

Fig. 20: Dupree, South Dakota Storm Case: 11 June 1976,
Queen Air (Q.A.) mid-level (16,000 ft. MSL)
Flight Track.

The symbols are the same as in Figs. 11 & 12.



squall line on the back (west) side, which in this case required a definite anticyclonic curvature of the flow. Thus, it is apparent that the near cloud flow field is not necessarily the same as that derived from synoptic scale analysis which indicated a general flow from the southwest.

(b) As a consequence of (a) above, there appears to be no inflow into the upstream side of the cells at this mid-storm level (16,000 ft. MSL). This has been our experience on several other severe storm systems which is not in agreement with many descriptive (Browning, 1964) and theoretical (Klemp et al, 1981) storm models. Thus the downdraft air below cloud base which may have θ_E 's similar to the upstream, mid-level air must in some case have a different origin.

(c) In general, the air temperatures (2° - 4° C) indicate that the thermal field at 16,000 ft. MSL is very nearly constant along the flight track except for the initial phases where temperatures were slightly higher (0° - 2° C) due to slightly lower altitudes (15,200-15,700 ft. MSL). On the other hand, the dew points show a definite decrease throughout the course of the flight track (Fig. 20). After 2314Z the dew points were generally -35° C whereas prior to this time they varied from -28° to -30° C. The storm appeared to reach its period of greatest development and intensity after 2315Z. We suspect that during these later stages of the flight there was weak subsidence in close proximity to the back-building cirrus shield which acted to bring drier air to the lower mid-levels. We have previously observed such descending flow in the close

proximity of a large number of storms at both mid and upper levels (Sinclair, 1973).

D. 12 June: Redwood Falls, Minn. Storm Case

1. Synoptic Weather Situation

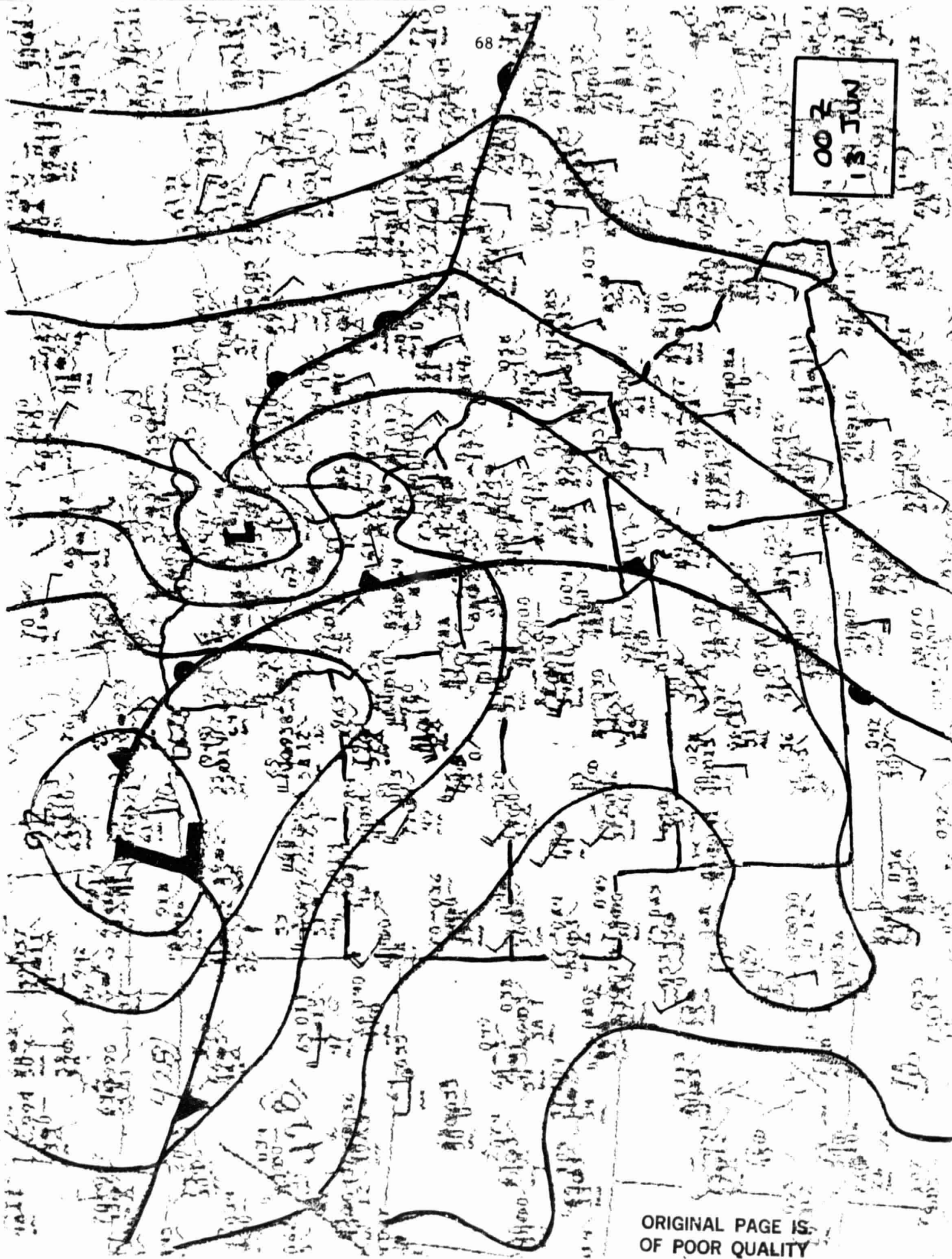
The low pressure center and associated cold frontal system on 11 June had moved northwest and west to northern North Dakota and extreme eastern South Dakota, respectively by mid-afternoon on the 12th (Fig. 21). The frontal system extended from the Canadian border into Texas, thereby providing an extensive N-S division between the warm, moist Gulf air ahead of the front and the more continental air behind the frontal zone. The upper air flow (Fig. 22) was again, as on 11 June, from a southwesterly or southerly direction. However, the flow was much stronger with larger shear at all levels in the research area. The Radar Summary Chart (Fig. 23) shows the type and intensity of the storm activity that was present in the research area some 5-6 hours before the research flights were conducted. Cloud tops in the research area exceeded 55,000 ft. MSL during the aircraft measurement period.

2. Aircraft Deployment

The Q.A. and T-28 departed Pierre, S.D. for Minneapolis, Minn. at 1000 CDT (12 June) for research flights ahead of the frontal system that produced the Dupree, S.D. Storm Case (11 June). The aircraft penetrated the frontal zone and associated C_b clouds near Redwood Falls, Minn., landing Minneapolis at 1200 CDT. The NASA Learjet arrived at 1330 CDT at which time we were advised to depart Minneapolis by 1430 CDT to investigate two squall lines developing to the west of the city. The Q.A. and T-28 departed Minneapolis at 1357 CDT and 1415 CDT, respectively for the developing squall line near Redwood Falls, Minn. (Fig. 24). The NASA Learjets departed at approximately 1430 CDT. Both the Q.A. and the

Fig. 21: 13 June 1976, 0000Z Surface Chart

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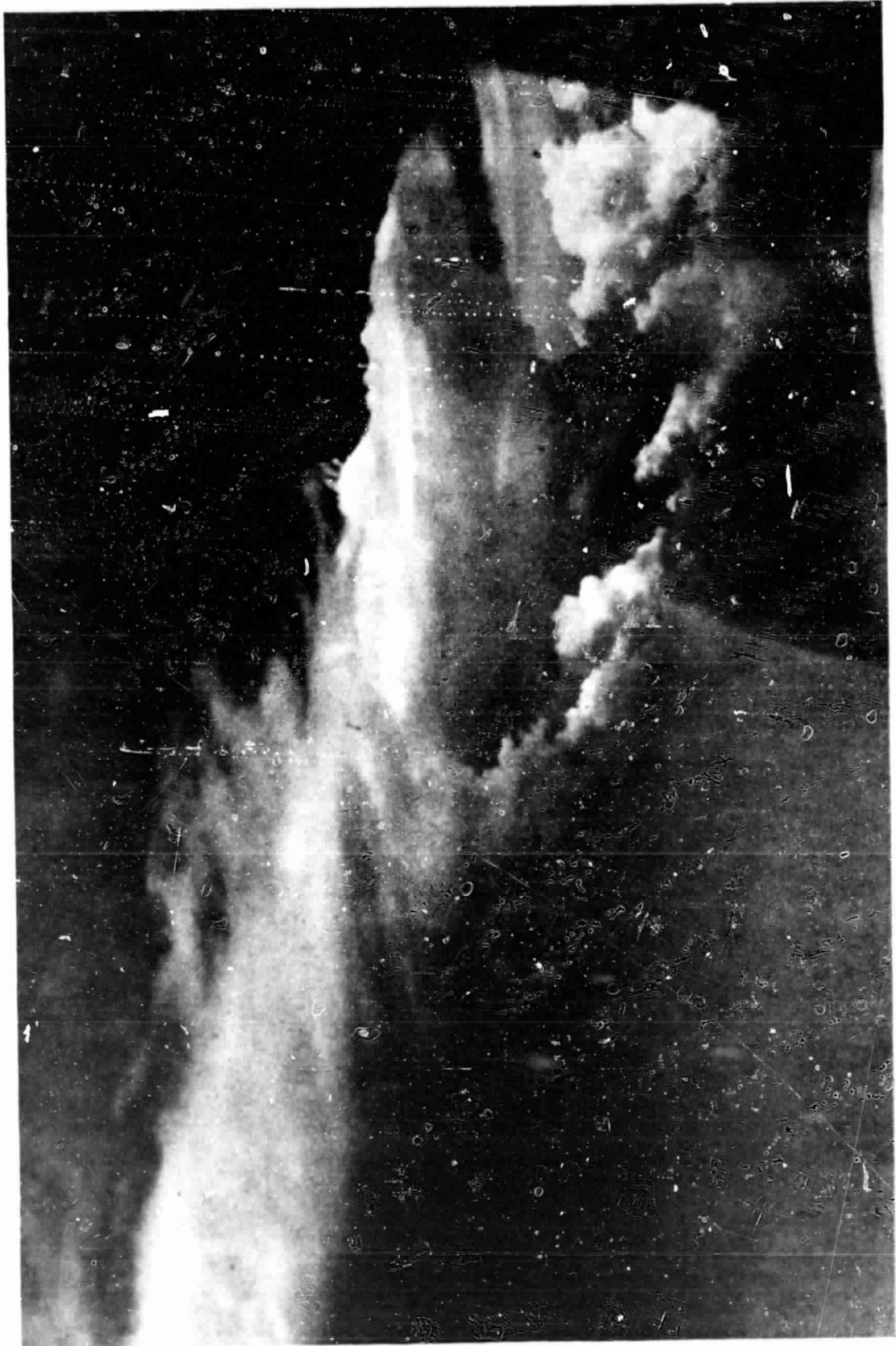


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Fig. 22: 13 June 1976, 0000Z 500 mb Upper Air Chart

Fig. 23: 13 June 1976, 0435Z Radar Summary Chart

Fig. 24: Developing line of cells near Redwood Falls,
Minn. from Queen Air research aircraft.



T-28 research aircraft obtained excellent sub-cloud and mid-level measurements along a line of severe storm cells that produced overshooting tops exceeding 55,000 ft. MSL (Fig. 24). At the completion of the measurement period, both the Q.A. and T-28 aircraft returned to Minneapolis while the NASA Learjets went to Omaha, Neb. and Chicago, Ill.

3. Cloud Base Measurements: T-28 Research Aircraft

At 2043Z (1443 CDT), the T-28 commenced taking measurements along the east side of the line of developing storm cells which were forming just east of Redwood Falls VOR (Fig. 25, F.T.#1). After the completion of one sub-cloud flight track (2043Z-2055Z) it was apparent that the entire downstream (eastern) boundary of the line exhibited consistent outflow along the flight track (5,000 ft. \pm 800 ft. MSL). As a result, the following series of flight tracks were moved around the southern edge of the storm to the upstream (western) side of the line in order to probe the inflow-updraft region. Some of the more important features of flight tracks #2-#4 (Figs. 26-28) are outlined below:

(a) The analysis of flight track #2 data clearly indicates that there is strong southwesterly inflow on the southern edge of the squall line (Fig. 26). The mean updraft measurements along the flight tracks show a definite increase (+5 to +10 to +13 m sec⁻¹) as the main updraft core located just to the south of the heavy precipitation area is approached. Since the inflow air is sometimes highly turbulent, the downdraft components also increase in the inflow as it approaches the main updraft core, i.e. the downdraft velocities increased from -1 to -2 to -5 m sec⁻¹ (ref. flight track #2, Fig. 26). Note also that the inflow appears to be diverted to the right and around the heavy precipitation core which outlines the downdraft region. The inflow air for flight track #2

Figs. 25 - 28: Cloud base measurements: T-28 research aircraft.

The symbols are the same as in Figs. 11 & 12.

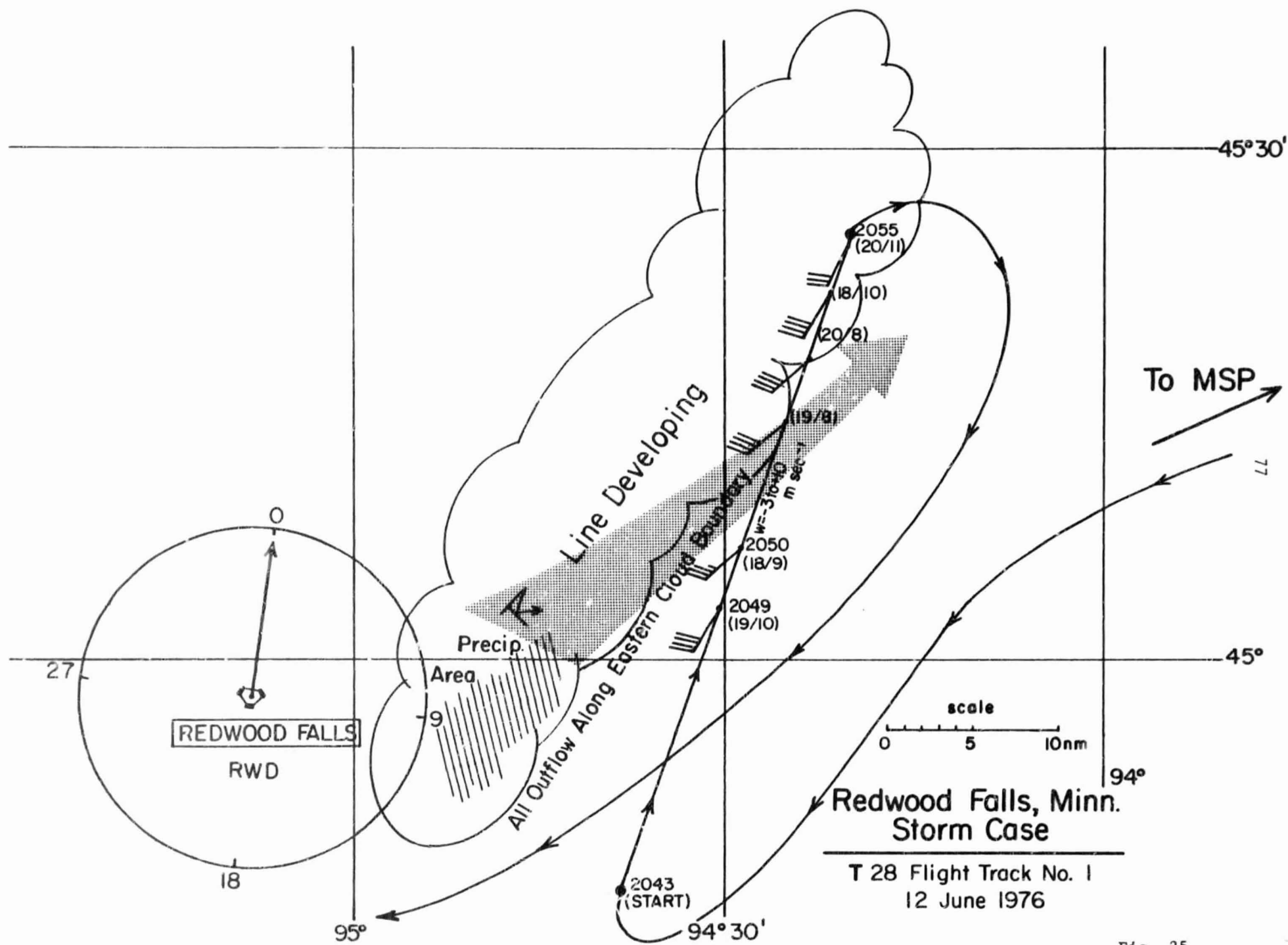


Fig. 25

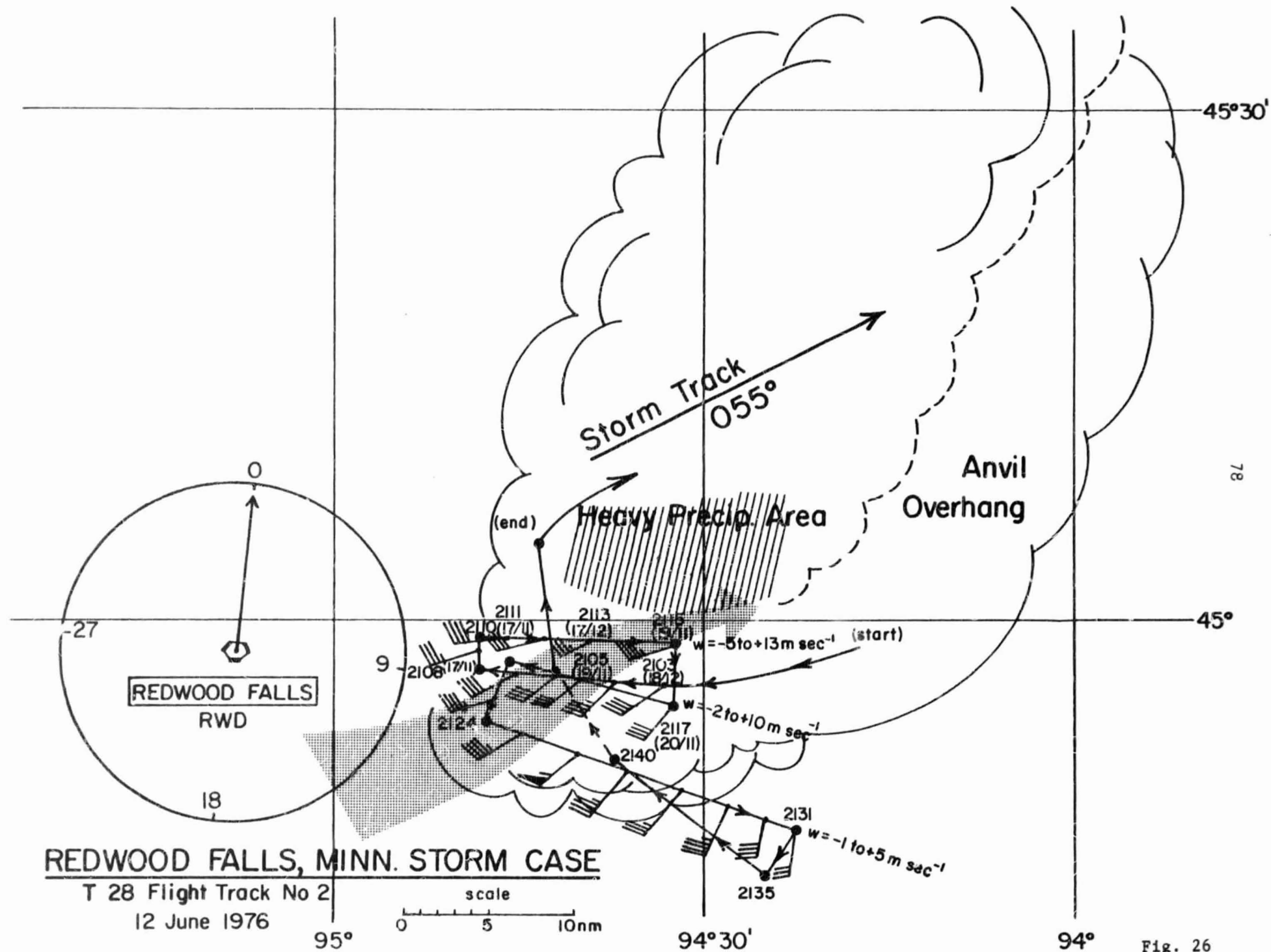


Fig. 26

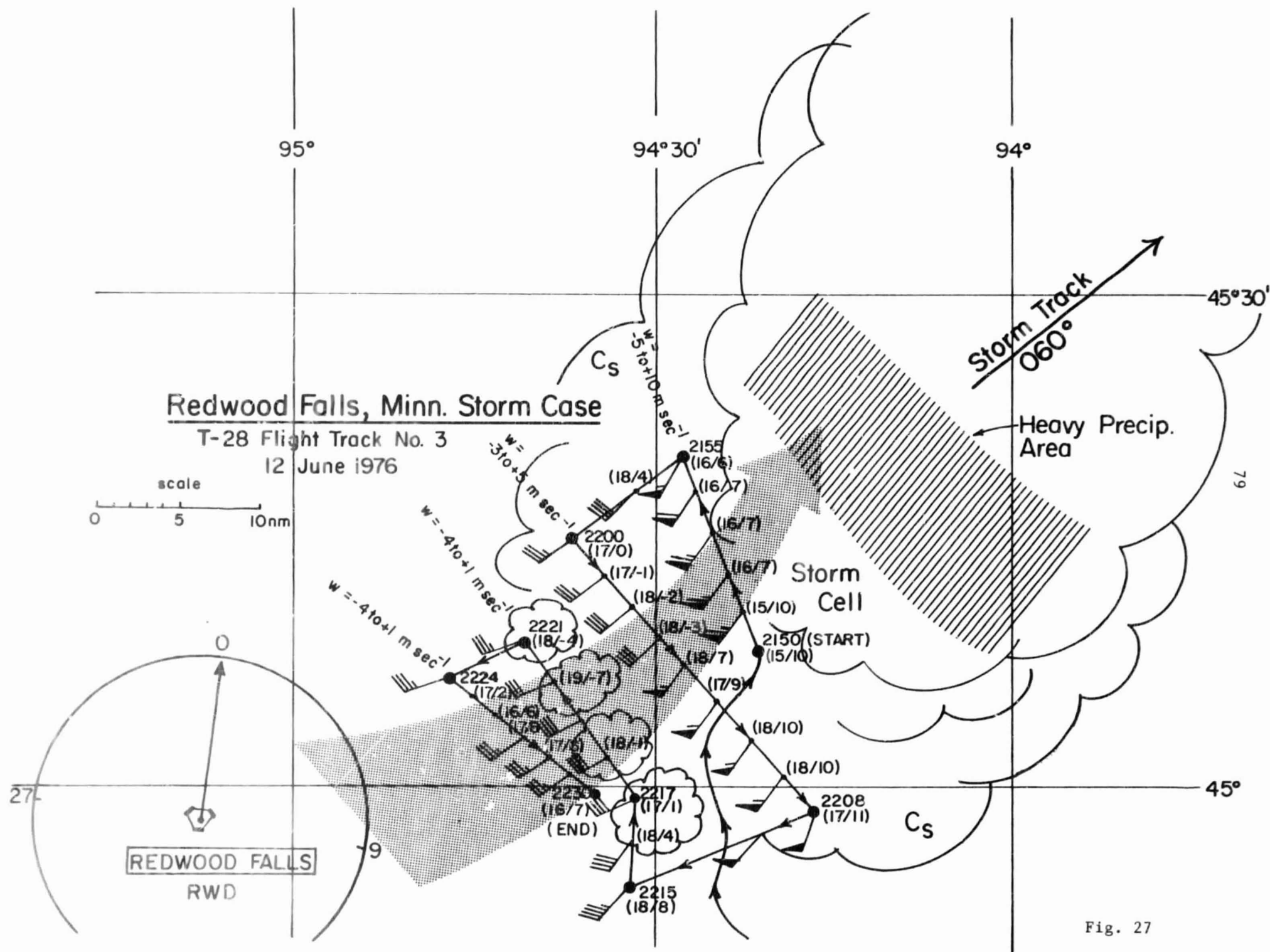
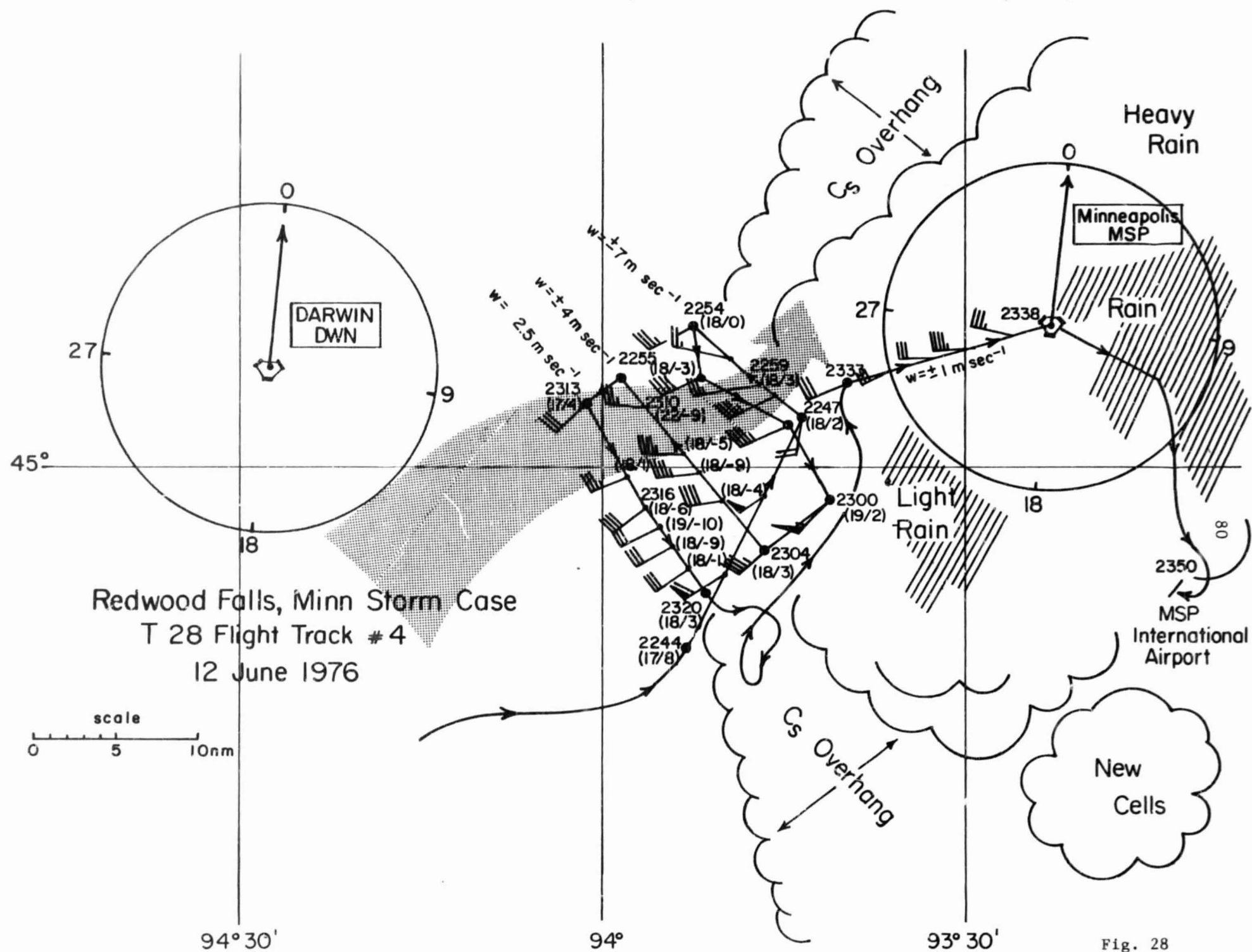


Fig. 27



(Fig. 26) is not significantly different in temperature and dew point from that of the outflow air (flight track #1, Fig. 25) when the slightly different altitudes are taken into account.

(b) Flight track #3 (Fig. 27) was conducted primarily on the upstream (western) flank of the storm. Here the inflow was significantly stronger than on the southern edge but still directed toward the heavy precipitation - downdraft area. However, the inflow air in this case appears to be diverted around the opposite (western) edge of the precipitation core. The temperature of the inflow air is again not significantly different from that of flight track #2. However, the dew points show appreciably drying of the air in the center of flight track #3. Note especially the -1° to -7°C dew points which suggests subsidence near the cloud boundary. The subsidence is verified by the vertical motion measurements which show up to -4 m sec^{-1} downdrafts along these track segments with low dew points.

(c) Flight track #4 (Fig. 28) represents a final series of inflow - updraft probing by the cloud base aircraft. During this time (2248Z-2338Z) the wind speeds within the inflow region have decreased slightly from those of flight track #3 and the storm appears to be in its dissipation stage. The updraft core is not as well defined as that experienced during flight tracks #2 & #3 - note the more chaotic vertical motion (w) field indicated by w's varying from ± 2.5 to ± 4 to $\pm 7 \text{ m sec}^{-1}$ along the track segments. The subsidence and low dew points of the inflow air shown in Fig. 27 (flight track #3) appears again along the two outer track segments where dew points of -6° to -10°C are found. This descending air appears to be close to the main cloud boundary and near the

edge of the upper cirrus (C_g) overhang. This series of sub-cloud measurements clearly show that these severe storm cells were back-feeder types, i.e. the inflow was on the back (western) side and the outflow took place along the front (eastern) boundaries of the cells.

4. Mid-Level (16,000 ft. MSL) Measurements: Queen Air Research Aircraft

The Queen Air (Q.A.) research aircraft was advised at 2100Z by Lear 1 that the storm was located on the 135° radial at 22nm from the Redwood Falls (RWF), VOR which was later revised to the 140° radial at 70nm at 2037Z. The Q.A. located the storm at 2043Z on the 110° radial at 19nm from RWF with the aircraft weather radar. Successive closed circuits were flown by the Q.A. to obtain wind, temperature, and moisture data in the clear air at mid-levels to the rear of the line of severe storm cells (Fig. 29). The data analysis indicates:

(a) As in the Dupree Storm Case, the mid-level flow is essentially parallel to the storm line and/or the direction of cell movement (Fig. 29). If the storm cell motion is taken into account, the relative winds would indicate a divergent flow pattern on the upstream side of the squall line.

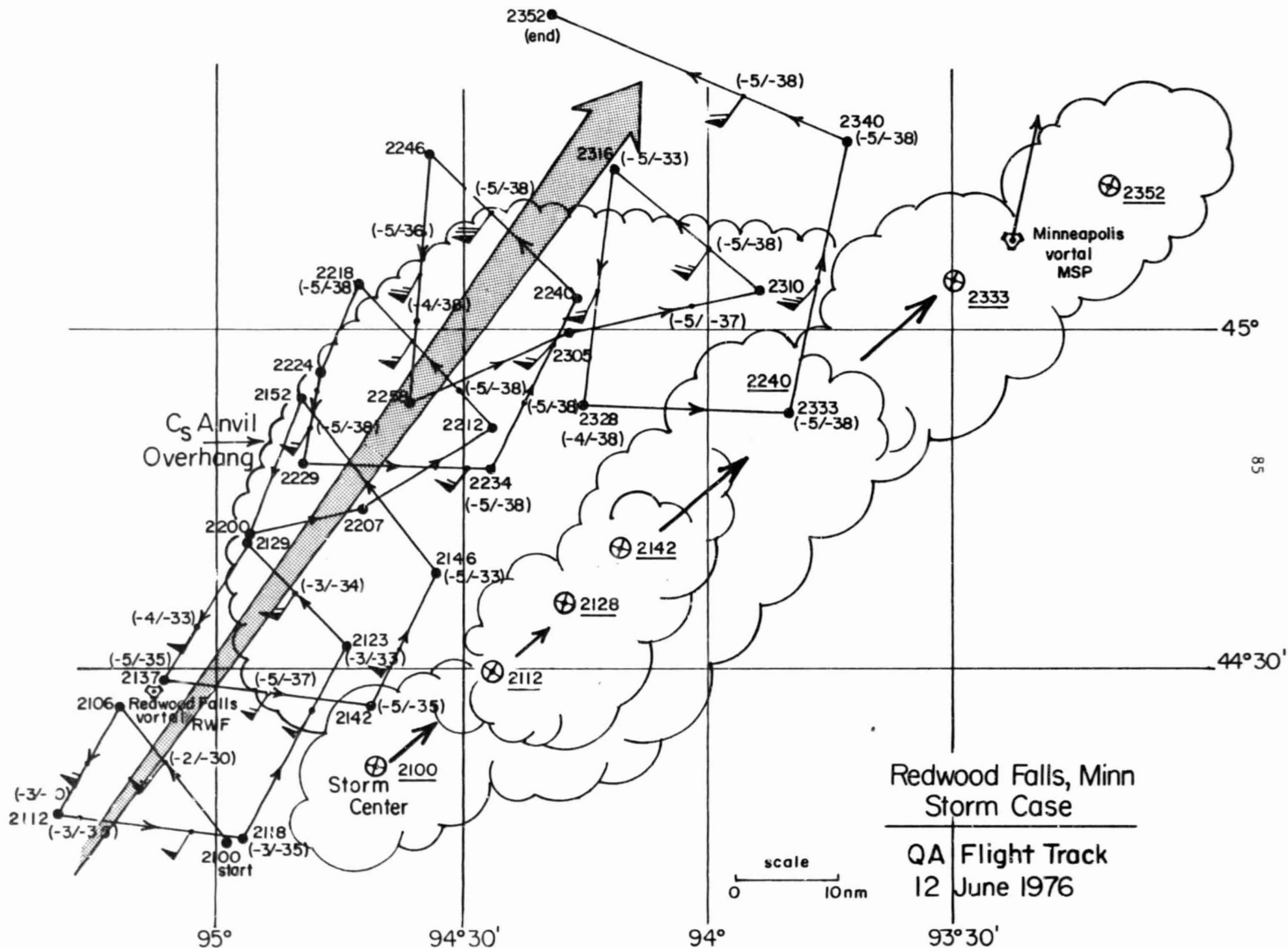
(b) The upstream flow pattern, absolute or relative, therefore indicates no organized inflow to the back (west) side of the storm cells at mid-levels (16,000 ft. MSL). Again, as in the Dupree, S.D. Storm Case, it appears that the downdraft air in or near the precipitation core does not originate at this upstream level.

(c) The air temperatures do not vary significantly (-3 to -5°C) along the flight track. The dew points also show little significant variation ($\pm 9\%$) with the later part of the track indicating slightly drier air than at the beginning of the flight.

Note that most of the flight track was made below a cirrus anvil overhang (Fig. 29) that had built back into the upper air flow from the cells downstream during the course of the flight. It is interesting to note, however, that as in the Dupree, S.D. Storm Case the temperatures are much warmer (-3° to -5°C) and the dew points (-30° to -38°C) somewhat lower than that deduced from the synoptic chart (500mb) data (Fig. 22) which indicates $T \approx -16^{\circ}\text{C}$ and $T_d \approx -28^{\circ}\text{C}$. Subsidence below the C_s overhang may be responsible for part of this discrepancy.

Fig. 29: Redwood Falls, Minn. Storm Case: 12 June 1976
Queen Air (Q.A.) mid-level (16,000 ft. MSL)
Flight Tracks.

The symbols are the same as in Figs. 11 & 12.



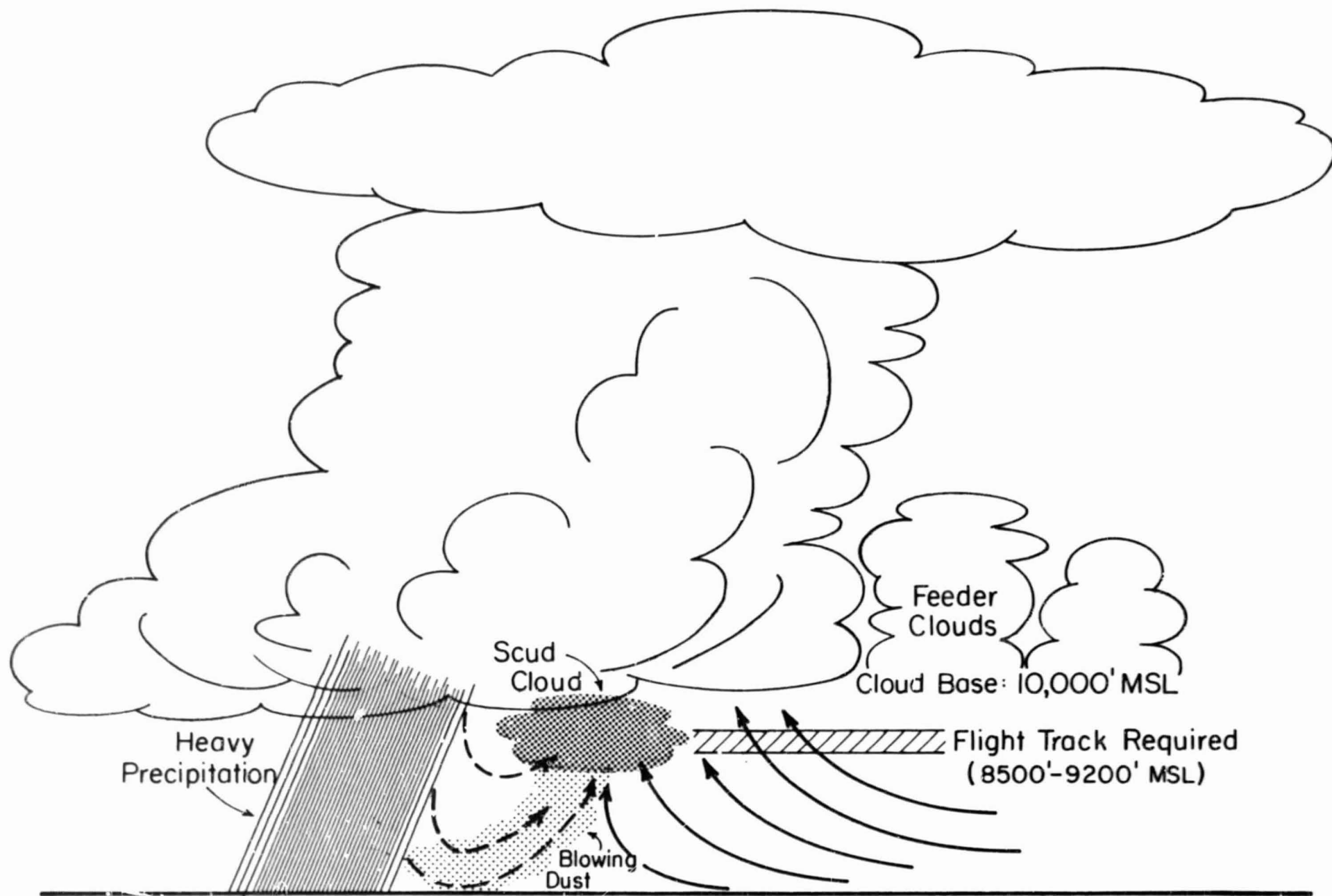
V. Summary and Conclusions:

A. Significant Results

1. A new concept of aircraft deployment for severe storm research has been further refined and developed from our experiences during the 1975 and 1976 SSSP's. This unique mobility capability allowed us to move calibrated research aircraft with crews and scientific personnel on a 48 hr. alert schedule to any location with a radius of 1000 nm of our operating base at Fort Collins, Colo. This particular operational capability requires careful planning and execution in that it involves the research aircraft, the flight and ground crews, the scientific personnel, the logistics of long moves, the close coordination with the FAA for air traffic control, as well as the close coordination with NASA and Kansas City National Severe Storm Forecast Center. The aircraft-instrumentation status and the aircraft mobility schedule during the field experiment period are documented in Table I.

2. One of the more important scientific aspects of the field measurements concerns the recirculation phenomenon of the downdraft air back into the updraft core. We have observed this storm characteristic many times in the past and it is explicitly evident in the Cometa, Texas and the Redwood Falls, Minn. Storm Cases (Fig. 12 and 18). For a front-feeder type of storm, this recirculation of the precipitation downdraft air into the main updraft core is schematically shown in Fig. 30. This relatively cool, moist downdraft air from the heavy precipitation core is easily tracked into the updraft core (which is usually near the scud cloud) by visually following the wall of dust that is picked up by the outflow air near the ground. This wall of dust and its trajectory is quite visible at the flight levels of the cloud base aircraft (T-28).

Fig. 30: Typical front-feeder storm cell.



For a back feeder type of storm such as the Lometa, Texas Case, the updraft core is on the upstream side of the cloud and hence the outflow from the heavy precipitation core recirculates dust laden air back into the updraft as shown in Fig. 12. This recirculation of the precipitation core downdraft air back into the updraft core (front and/or back-feeder storm type) appears to be an important component in sustaining storm growth and duration which is relatively independent of outside environmental factors.

3. In addition to the recirculation of downdraft precipitation core air back into the updraft region as explained in (2) above, the downdraft-outflow air ahead of the storm (back-feeder type) may also recirculate back into the updraft region as shown in Fig. 12. This recirculation of storm outflow air takes place over a much larger horizontal scale than that involved in the precipitation core recirculation.

Note that the outflow air at the measurement level in Fig. 12 is not significantly cooler or more moist than the inflow air. We suspect this is not the case for the precipitation core recirculation flow. Thus, the storm cells may have two separate pathways for recirculating 'old' storm air back into the inflow-updraft region and thereby sustaining the storm growth and extending its life-cycle. However, many more measurements in the storm subcloud region are required before these features can have statistical credibility.

4. The sub-cloud vortex flow of the Lometa, Texas Storm Case (Figs. 11 and 12) indicates that sufficient vorticity (vertical component) may be readily available in the near storm environment due to the interaction of the outflow and inflow. Consequently, intricate models of vorticity generation (vertical component) by use of vortex tubes and, twisting terms may not be physically relevant. If this vortex

($\zeta \approx 10^{-3} \text{ sec}^{-1}$) center moves into the inflow-updraft region, vertical stretching of the vortex flow will take place leading to rapid vortex intensification and possibly tornado genesis. Thus, some of Ferrel's (1889) original concepts may still be valid.

5. The mid-level, upstream measurements indicate parallel (absolute velocities) flow with respect to the storm cell and line motion. Consequently, there appears to be little or no mid-level (clear air) inflow into or around the cells. This conclusion is at variance with a large number of descriptive and/or numerical models which specifically relate the origin of the downdraft air at sub-cloud levels to mid-level, inflow air on the back side of the storm. However, we suspect that the origin of the downdraft air at sub-cloud levels is to be found within the storm interior. Verification of either of these two hypotheses could be obtained by series of cloud base and storm environment measurements.

6. The analysis of the Dupree, S.D. and Redwood Falls, Minn. Storm Cases (Figs. 17-19 and 25-28) clearly shows that the squall lines and embedded cells can change from a front-feeder to a back-feeder type within a 24 hour period. This is the first time we have had the occasion to observe such a transformation. Our previous experience has been that storms within a certain region exhibit a particular type of inflow characteristic and orientation. For example, northeastern Colorado storms are usually front-feeder types, i.e. the inflow of warm, moist air enters the sub-cloud region from a southeasterly direction. A back-feeder storm in this area would experience inflow of warm, relatively dry air into the updraft region. Consequently, these storms have difficulty developing significant vertical structure. The explanation for the Dupree - Redwood Falls inflow transformation is still not clear, although we believe that it was controlled primarily by meso-synoptic

scale dynamics.

7. The results of the storm spherics research conducted by Dr. B. Wilson of Georgia Institute of Technology (NASA sub-contract) with the CSU Queen Air research aircraft will be reported to NASA in a separate Georgia Tech. Final Report.

B. Future Program Improvements

1. As in the 1975 SSSP, considerable improvement in the field communications is required in order to keep the sometimes widely dispersed aircraft and crews informed of the deployment schedule. Again this year we experienced difficulty in reaching the Project Director and/or his assistant prior to or during the aircraft deployment - this was especially evident when the CSU aircraft were directed to an airport that was different than that used by the NASA Learjets. These communication gaps could be completely or at least partially eliminated by requiring that the Learjets land and deploy from the same airports selected for the CSU aircraft. This would not only improve the daily flight scheduling but would also permit the establishment of a debriefing meeting immediately after the individual storm flights when the information is fresh in the minds of the flight crews and scientific personnel.

2. An improvement in the Learjet vectoring of CSU aircraft to the selected storm cell is also desirable. It is suggested that the Learjets carry a complete supplement of Low Altitude charts for use in establishing optimum VORTAC vectors to the storm cell for the low altitude aircraft.

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